6. CHAPTER 6: EFFICIENT AND EQUITABLE FLOOD INSURANCE MARKET STRUCTURES UNDER CLIMATE CHANGE[1]

Abstract

Flood risk in Europe will increase due to climate change and growth in economic exposure and adequate insurance schemes are needed to in order to adapt. Insurance markets will face challenges in remaining viable and affordable. Insurance markets may need reform to offer affordable financial protection while providing incentives for risk reduction. Here, it is shown that the average risk-based flood insurance premium could double between 2015 and 2055. The affordability of insurance can be improved by the key features of Public-Private Partnerships (PPPs) through public reinsurance and limited premium cross-subsidization. In addition, such a structure includes incentives for risk reduction by households. While, modelled premiums differ widely across insurance structures, reform toward PPPs could limit unaffordability problems to 16% of European population at high risk. These findings were evaluated in a comprehensive sensitivity analysis, supporting ongoing reforms that move towards risk-based premiums, strengthen purchase requirements, and engage in multi-stakeholder partnerships.

[1] This chapter is based on: Hudson, P., Botzen, W.J.W., Aerts, J.C.J.H., 2017. Efficient and Equitable Flood Insurance Arrangements to Cope with Increasing Flood Risk under Climate Change. *In review*. VU University, Amsterdam.

6.1 Introduction

The previous chapters have noted the importance of flooding and the potential benefits of insurance coverage for managing and reducing flood risk. However, due to the increasing trend in flood risk there is growing pressure on insurance markets (Mechler et al., 2014). This has initiated discussions about insurance market reforms in Europe (Surminski et al., 2015) and in the U.S. (Michel-Kerjan and Kunreuther, 2011). In the U.S., it has been debated whether private insurers can play a larger role (Michel-Kerjan et al., 2015) in covering flood risk and how to provide better risk reduction incentives (Kunreuther, 2016). European countries have their own separate flood damage compensation arrangements. The diversity of these arrangements was highlighted in the debates surrounding the European Commission Green Paper on disaster insurance (EC, 2013).

One debated feature in the Green Paper was the desirability of risk-based insurance premiums compared to flat insurance premiums, which do not depend on the specific risk faced by the policyholder. A disadvantage of risk-based premiums is that premiums must increase in high-risk areas, which may conflict with the affordability of insurance (DEFRA, 2011; Kousky and Kunreuther, 2013; Chapter 5). However, risk-based premiums may incentivize the implementation of risk reduction measures, by rewarding those who take measures that reduce their risk. Such measures include flood-proofing homes using water-resistant materials or installing flood shields. These will become more important as future flood risk increases as a result of climate change (Jongman et al., 2015).

The Green Paper also proposed potential regulation to compulsory bundle natural disaster insurance with general homeowner's insurance (EC, 2013) in order to achieve broad coverage of many homeowners. Such bundling is similar to how the French natural hazard insurance market is structured (Paudel et al., 2012). However, the introduction of mandatory purchase requirements due to European level regulation is rather contentious (EP, 2014).

Discussions have also focused on the desirability of different degrees of government and private sector involvement in flood insurance. For instance, Austria has a pre-funded government catastrophe compensation fund (CCS, 2008), while, compensation is completely provided by private insurance companies in the UK. As another example France involves both the private and public sectors through a public-private sector partnership (PPP) (Poussin et al., 2013).

An evaluation of flood insurance market structures in terms of economic efficiency and equity, and their capacity to cope with increasing flood risks, is lacking. We, therefore, examine suitable directions for reform of flood insurance markets using four criteria that reflect ongoing discussions (Table 6.1): (a) The cost for low-risk households that risk sharing between low and high-risk households entails: this implies that low-risk households are paying for insurance they gain no benefit from; (b) Incentivized risk reduction: premiums should reflect risk and promote risk reduction; (c) Insurance penetration rate: many flood-prone households should be covered by the insurance; (d) Unaffordability of insurance: there should be support for low-income households (e.g., Schwarze and Wagner, 2007; Paudel et al., 2012; Poussin et al., 2013, DEFRA, 2011; EC, 2013; Michel-Kerjan and Kunreuther, 2011). Meeting these outcomes results in trade-offs across the criteria.

6.2 Methods

The Dynamic Integrated Flood Insurance Model (DIFI) is used to model the following outcomes for two time periods (2015–2035 and 2035–2055) in order to find the most suitable flood insurance market structure: insurance penetration rate, incentivized risk reduction, magnitude of unaffordability of premiums, and the premium cost for low-risk households due to risk sharing. The most suitable market structure is the one that best manages the trade-offs between the modelled outcomes. Chapter 6 focus on flood insurance coverage for high-risk households because the policy debate commonly focusses upon this group.

The DIFI model, involves coupling a model of the insurance sector and consumer behaviour with a spatially explicit probabilistic flood risk model that extends the model presented in Chapter 5. The DIFI model calculates flood insurance premiums and simulates consumer behaviour dependent on the flood insurance market structure. Consumer decisions involve purchasing insurance and investing in flood damage mitigation measures. The DIFI model accounts for insurance incentives for household-level risk reduction by including premium discounts for household-level risk reduction. The resulting aggregated household risk reduction lowers the overall level of flood risk.

Results were obtained for two periods: 2015–2035 and 2035–2055. The regional scale output from the DIFI model was aggregated to the national level to evaluate the most suitable market structure per country. This was done in a multi-criteria analysis (MCA), which is used to aggregate DIFI model scores for individual criteria (Table 6.1) into an overall country score that balances the trade-offs between these criteria. The general modelling framework is displayed in Figure 6.1 and described in more detail in the following sections.

Table 6.1 Summary and definition of the evaluation criteria estimated by the DIFI model

	Definition	**Benefit/Cost**	**Aspect**
Criterion 1: Cost on low-risk households	The total NPV of the risks of high-risk households paid by low-risk households	Cost	Equity
Criterion 2: Incentivized risk reduction	The total NPV of incentivized risk reduction conducted by households	Benefit	Economic efficiency
Criterion 3: Insurance penetration rate	The average percentage of households with high flood risk that buy insurance	Benefit	Economic efficiency
Criterion 4: Unaffordability of insurance	The NPV of the magnitude of unaffordability, measured as the portion of premiums that cannot be paid from a poverty adjusted disposable income	Cost	Equity

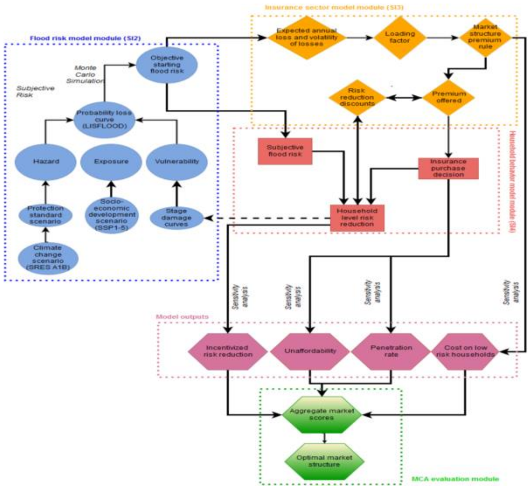

Figure 6.1 Flow chart of the Dynamic integrated flood and insurance (DIFI) model version 1.0 modelling scheme

Notes: Blue circles represent the flood risk model component, red diamonds represent insurer behaviour, red rectangles represent policyholder behaviour. green hexagons represent the multi-criteria analysis. The combined flood risk model, insurer and policyholder behaviour elements form the DIFI model. A key finding is that increasing flood risk implies that the most suitable market structure has the following characteristics: premium cross-subsidization with a limited premium cost for low-risk households; involvement of the government as reinsurer, which creates a PPP market; incentives for household risk reduction through premium discounts for flood-proofing homes; purchase requirements, such as mandating flood coverage or informal requirements that connect coverage with mortgages or rental agreements, or tying flood insurance purchase to a more commonly acquired insurance policy (such as fire). The model predicts that, by 2035, most countries will move towards reforms introducing public reinsurance and purchase requirements, while by 2055 the majority of countries will favour continued reform into a full PPP market structure. For about a third of the EU, the model framework estimates a reform pathway that does not involve a single optimal market structure for different time periods, but instead evolves over time when flood risk changes.

The DIFI model has several steps, which are summarized here and explained in detail in the following sections:

1. The expected annual flood loss and variance of losses is simulated at a 100m x100m scale across Europe using an adaptation (described in Section 6.2.1) of the European flood risk model developed by Feyen et al. (2012) and Rojas et al. (2012). Risk simulations are then aggregated to NUTS 2 regions.
2. The expected annual loss and the variance of losses for NUTS 2 regions are converted into household insurance premiums for the modelled market structures based on the flood insurance model presented in Paudel et al. (2013), and Paudel et al. (2015) and adapted in Chapter 5 (see Section 6.2.2 for the relevant modifications). There are six selected market structures, which are stylized versions of flood insurance market features, as distilled from extensive literature reviews (see, among others, Paudel et al., 2012; Maccaferri et al., 2012; CCS, 2008). Table 6.2 presents the stylized market structures.
3. The behaviour of households at risk of flooding is based on the concept of subjective expected utility (Savage, 1954) and the model presented in Chapter 5 under a given scenario of household flood risk perceptions for each flood insurance market structure. Household flood risk perceptions consist of two elements: subjective flood occurrence probabilities and subjective perceptions of the reduction in flood risk that can be achieved with flood-proofing measures. For each household at risk within a NUTS 2 region at risk of flooding, behaviour is modelled in the following manner:
    3.1. The subjective flood probability occurrence scenario is based on three sources of data: Botzen et al. (2009), Botzen et al. (2015) and the German Insurance Association (GDV) (2013). Botzen et al. (2009) and Botzen et al. (2015) investigated and compared households' subjective flood occurrence probability and the objective flood occurrence probability. Subjective flood occurrences are complemented by perceived flood impact based on a calibrated distribution from the data presented in GDV (2013). The subjective flood

occurrence scenario is combined with one of three different scenarios of individual perceptions of risk reduction from flood-proofing. These risk reduction perception scenarios are based on three empirical studies of households in flood-prone regions in the EU (Kreibich et al., 2005; Bubeck et al., 2012; Poussin et al., 2014). Each of these studies conducted surveys of flood-prone regions to collect empirical information on the type of flood preparedness measures that each household has employed, on the basis of which a distribution of perceptions of risk reduction has been calibrated. The final outcomes of this step are three combined flood risk perception scenarios.

3.2. A household decides if it will employ a flood risk reduction measure based on a subjective cost-benefit analysis and employs a measure if it is economically desirable and also affordable. This step generates the baseline level of achieved risk reduction, which is used for judging the effectiveness of insurance incentives at stimulating the implementation of additional risk reduction measures.

3.3. The same household then decides if it will buy an insurance policy based on the market structure, discounts for the risk reduction measures, their subjective flood risk perceptions, and the affordability of insurance premiums given the household's income.

3.4. If the household buys an insurance policy, it is eligible for a risk reduction incentive in the form of a premium discount from the insurer. The household will employ a risk reduction measure if the measures are cost-effective with this incentive and did not employ the risk reduction measure before. The potential discount offered by insurers is based on estimates provided in Chapter 3 and Chapter 5.

4. After modelling the behaviour for each household across all NUTS 2 regions, the values of the following criteria are aggregated to the national level for each insurance market structure (for a 20-year period): the national mean insurance penetration rate, the magnitude of unaffordability, the cost for low-risk households due to the market structure's degree of risk sharing, the mean degree of incentivized risk reduction. This step is completed for all three combined flood risk perception scenarios, and the ensemble mean across the flood risk perception scenarios for the criteria is calculated.

5. The ensemble mean values of the criteria are then placed in a multi-criteria-style analysis in order to evaluate the preferred market structure through the following steps:

   5.1. The ensemble mean values are standardized across market structures within a country on a [0, 1] scale. The closer a standardized criterion value is to 1, the better the market structure performs on that criterion as compared to the other market structures.

   5.2. The standardized values are weighted and summed to produce a final overall score for each market structure within a country on a [0, 1] scale.

   5.3. The market structure within a country with the highest overall weighted score is deemed to be the most suitable market structure.

6.2.1 Flood risk model

The underlying flood risk model used in this chapter is the same as presented in Chapter 5. There are several small differences however. The first is the geographical spread has increased to cover most of Europe while focusing on those (potentially) affected by the flood with an occurrence probability of 1%. The second difference is that rather than the integral of the fitted power-law function, a Monte Carlo simulation (of 1,000,000 draws) produces an estimate of the annual expected flood loss per household and the variance of losses[2]. The randomly drawn floods still must exceed the level of protection in place in order to cause damage, as noted in eq. (6.1). It is assumed that protection standards are fixed over time implying that governments maintain a constant flood occurrence probability by altering protection infrastructure as required (the same assumption as in Chapter 5). The values of PS_j used are taken from Jongman et al. (2014).

$$L(p)_{j,t} = \frac{f\left(H(p)_{j,t}, E_{j,t}, V_{j,t}\right)}{N_{j,t}} | PS_j \qquad (6.1)$$

[2] A Monte Carlo analysis was used in order to match the process used to estimate the flood insurance purchase decision of households.

Similar to Chapter 5, changes in the flood hazard over time were simulated using climate change projections based on the SRES A1 greenhouse gas emissions scenario, as produced by CIESIN. The future value of exposed assets and population were again estimated by rescaling impacts through the ratio of the future and baseline real GDP or population. Land use classifications are assumed to remain constant over time, which means that changes in exposure alter the value of land parcels. The main departure from Chapter 5 is that rather than rescaling according to the SRES A1 scenario, the ensemble mean of the various shared Socioeconomic Pathways (SSP) scenarios as provided by IIASA[3] was used instead. For Western Europe, there is not a large difference between the projected losses per household between rescaling using the SSP or SRES projections, while for Eastern Europe the SSP scenarios produce more realistic socio-economic development pathways given observed current socio-economic trends. The use of a SRES socio-economic projection is examined in the sensitivity analysis (Section 6.3.3.2).

6.2.2 Insurance sector model

The insurer element of the DIFI model consists of several components that are investigated for each country. The first element to be determined is how the base risk element of insurance premiums differs across market structures (Section 6.2.2.1). Next, the potential behaviour of insurers must be considered. The main questions for insurers to consider is what cost or profit loading factors they will place on the risk element of an insurance premium (Section 6.2.2.2) or what potential discounts insurers will offer to households that employ risk reduction measures (Section 6.2.2.3). Finally, as this study is concerned with high-risk households, it must account for the potential explicit or implicit subsidization of high-risk households' insurance premiums through increasing insurance premiums of households with a low flood risk (Section 6.2.2.4).

It is assumed that each country under investigation has an insurance market that is willing to provide, and capable of providing, flood insurance to consumers as long as the consumer pays the offered premium[4]. This chapter only considers an insurer's underwriting business and not possible investment decisions and their desire to engage in the flood insurance market. The consumers and insurance products are defined over the high-risk households. In all modelled insurance market structures, the insurance premium is calculated at the start of the year under investigation and is set at that value until the next year before considering household-level risk reduction. Only households that employ risk reduction measures can receive premium discounts equal to the average reduction in flood risk that these measures achieve. This assumption maintains a flow of insurance premiums that matches the expected annual loss on average.

Based on a literature review, six stylized flood insurance market structures (M1–M6) (Table 6.2) are developed. Current flood insurance structures in European countries were assigned to M1–M3[5].

(M1) In solidarity public structures all households must buy an insurance policy at a fixed price, regardless of objective flood risk and personal preferences. Governments cover part of the flood risk and premiums are unconnected to risk.

(M2) The voluntary private market structure does not have this government coverage, allows households the free choice of whether to buy flood insurance, and offers risk-based premiums.

(M3) The semi-voluntary private market is similar, except that mortgage conditions require comprehensive insurance coverage, resulting in a high market penetration rate. These conditions imply that damages to buildings are almost universally insured, while contents within a building are less often insured.

[3] https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about
[4] This is not always the case.
[5] M4 is closely modelled on the UK flood Re scheme with the exception of a stronger connection to risk reduction than is currently in place.

In addition to these three existing structures, three new types of market structures (M4–M6) are proposed based on a public-private partnership (PPP) between the state and private insurers (see Table 6.2).

(M4) The semi- voluntary PPP is the semi-voluntary private market, except that it is supported by a public reinsurer. Introducing a public non-profit and risk-neutral reinsurer for the extreme portion of risk will limit insurance premiums for households.

(M5) The voluntary PPP has no purchase requirements, unlike the semi-voluntary PPP, which connects flood insurance coverage to mortgages or other purchase requirements.

(M6) The PPP market is a compromise between (M4) and (M5). It connects insurance coverage with mortgage (or rental) conditions, and premiums are risk-based unless the premium reaches a threshold amount at which the premium is capped. A capped premium is lower than the expected loss for high-risk households. In order to maintain insurer solvency, this shortfall is accounted for by placing a surcharge on the lower-risk households. The pool of high-risk households is also reinsured by a public reinsurer, which provides capital when losses exceed the expected loss that insurers must pay to households.

6.2.2.1 Market structures

The base structure of insurance premiums (across market structures) is based on that presented in Chapter 5. The premium that insurers charge households differs across market structures and takes the form displayed in eq. (6.2) where: $\pi_{i,j,t,s}$ represents the premium charged to household i in NUTS 2 region j at time t under market structure s, with s taking the value 1 for the solidarity market structure, 2 for the PPP market, 3 for the voluntary market structure, 4 for the semi-voluntary structure, 5 and 6 are the fully and semi-voluntary structures with a PPP respectively; ER_{DRR} is the discount (discussed in Section 6.2.2.3) that insurers will provide depending on the level of household risk reduction and $\bar{\pi}_{j,t,s}$ is the baseline average risk per household within a particular market structure for a given NUTS 2 region.

$$\pi_{i,j,t,s} = (1 - ER_{DRR})\bar{\pi}_{j,t,s} \quad (6.2)$$

Solidarity market

In this market the expected national annual loss (rather than the high-risk annual loss) is shared equally across all households in a nation regardless of individual risk. This results in a high degree of risk sharing between households and limits concerns about affordability. The insurance premium for the solidarity market structure is shown in eq. (6.3). In eq., (6.3) $D_{j,t}(p)$ stands for the total value of the deductible that must be paid by households for a flood event with an occurrence probability of p. Paudel et al. (2015) developed a model that estimates economically optimal deductible (reinsurance) levels for policyholders (insurers) and estimated an optimal deductible (reinsurance) level of about 15%. Therefore, $D_{j,t}(p) = 0.15$. The insurance premium is calculated as the average expected annual damage that the insurer will compensate over the range of damaging floods [0, PS_c]. The solidarity market employs the subscript c rather than j, as premiums are only differentiated at the national level. Losses are shared over the entire nation regardless of the risk levels faced by individual households.

$$\bar{\pi}_{c,t,1} = \frac{E\left(L_{c,t}(p) - D_{c,t}(p)\right)}{N_{c,t}} \quad (6.3)$$

Public-private market (PPP)

The premium for the PPP insurance market structure is presented in eq. (6.4). Eq. (6.4) introduces several additional terms: $\dot{\lambda}_{c,t}$, which is the cost-loading factor of the primary insurer; $\ddot{\lambda}_{c,t}$, which is the cost-loading factor of the public reinsurer operating within country c; the superscript RR, indicating the risk ceded by the primary insurer to the reinsurance market; r, which is the risk aversion coefficient of the private insurers; $\sigma_{0<a<99.8}$, which is the volatility of flood damage within the quantile range that is considered insurable (Paudel et al., 2015); $\bar{L}_{j,t}$ and $\bar{D}_{j,t}$, which are the modelled damage and deductible per high-risk household.

Table 6.2 A summary of flood insurance structures to which European countries are allocated

Structure group	Sector covering flood risk	Common market features	Countries allocated
M1. Solidarity public structure	Public	- Mandated purchase requirement - Premiums unconnected to risk - Very high penetration rate (100%) Government support for extreme losses	France; Belgium; Spain; Romania
M2. Semi-voluntary private market	Private	- Purchase is connected to mortgage lender conditions - Premiums are risk-based - High penetration rate (75%-100%) - Damage to buildings is more often insured than contents due to mortgage requirements No government support for extreme losses	Sweden; Ireland; UK; Hungary
M3. Voluntary private market	Private	- No government mandated purchase requirement (voluntary) - Premiums are risk-based - Medium to low penetration rates (25%-50%) if government support is uncertain (e.g., Germany) - Very low penetration rates (0%-25%) if government support is certain (e.g., Austria) - Possible government reinsurer rather than government compensation	Austria; Netherlands; Germany; Finland; Italy; Portugal; Luxembourg; Greece; Poland; Czech Republic; Slovakia; Slovenia; Croatia; Bulgaria; Latvia; Estonia; Lithuania
M4. Semi-voluntary PPP market	Public-Private	- Semi-voluntary market. Government reinsurer for extreme risk	Hypothetical market structure
M5. Voluntary PPP market	Public-Private	- Voluntary market - Government reinsurer for extreme risk	Hypothetical market structure

Finally, there is $CAP_{j,t}$, which is the maximum premium in region j at time t that insurers will provide through the formal cross-subsidization between high- and low-risk households.

$$\bar{\pi}_{j,t,2} = min \begin{cases} (1+\dot{\lambda}_{c,t})\left(E\left(\overline{L_{j,t}}(p) - \overline{D_{j,t}}(p)\right) + r * \sigma_{0<a<99.8}\right) + \left(1+\ddot{\lambda}_{c,t}\right)\left(E\left(\overline{L_{j,t}^{RR}}(p) - \overline{D_{j,t}^{RR}}(p)\right) + r * \sigma_{0<a<99.8}^{RR}\right) \\ (1+\ddot{\lambda}_{c,t})CAP_{j,t} \end{cases} \quad (6.4)$$

In the PPP market, households are offered premiums that are more strongly connected to the risk faced by high-risk households than in the solidarity market structure. This is because the premium is allowed to increase with risk until a certain point is reached, above which the premium is capped. The capped premium brings aspects of solidarity into this market structure. The first element of eq. (6.4) is the risk-based premium, while the second element is the capped insurance premium.

The value for $CAP_{j,t}$ is fixed for high-risk households within region j in a similar manner to the UK's Flood Re insurance pool for high-risk households. The Flood Re premium is set per household, with the most common potential cap being equal to £280 (30), which is approximately €311, or 1.8% of

2014 median British household income according to Eurostat[6]. A similar capped premium is applied by setting the capped premium equal to 1.8% of estimated regional median income. The cap increase over time is at the same rate as the change in the total value of exposure.

Voluntary or semi-voluntary market

The structure of the premium under the voluntary or semi-voluntary market structure is shown in eq. (6.5):

$$\bar{\pi}_{j,t,3} = (1 + \dot{\lambda}_{c,t})\left(E\left(\overline{L_{j,t}}(p) - \overline{D_{j,t}}(p)\right) + r * \sigma_{0<a<99.8}\right) + (1 + \ddot{\lambda}_{c,t})\left(E\left(\overline{L_{j,t}^{RR}}(p) - \overline{D_{j,t}^{RR}}(p)\right) + r * \sigma_{0<a<99.8}^{RR}\right) \quad (6,5)$$

The premiums are not cross-subsidized with low-risk households and, as such, the high-risk households are offered a premium that is risk-based, implying a full risk signal. The voluntary market structure can be altered by the introduction of a public-private sector partnership by replacing $\ddot{\lambda}_{c,t}$ with $\dddot{\lambda}_{c,t}$.

6.2.2.2 Competition and loading factors

In several structures, the insurance industry charges a loading factor ($\lambda_{c,t}$), as seen in the previous sections. Eq. (6.6) shows that $\lambda_{c,t}$ can be further subdivided into two elements: $C_{c,t}$ is the cost of providing an insurance policy, $\dot{PL}_{c,t}$ is the profit loading for primary insurers, and $\ddot{PL}_{c,t}$ is the profit loading for private reinsurance companies. The profit loading factors differ across layers of insurance, while $C_{c,t}$ is constant across layers.

$$\lambda_{j,t} = \begin{cases} \dot{\lambda}_{j,t} = C_{c,t} + \dot{PL}_{j,t} & if\ primary\ insurer \\ \ddot{\lambda}_{j,t} = C_{c,t} + \ddot{PL}_{j,t} & if\ private\ reinsurer \\ \dddot{\lambda}_{j,t} = C_{c,t} & if\ public\ reinsurer \end{cases} \quad (6.6)$$

Competition in primary insurance markets is assumed to follow Bertrand competition, whereby insurers compete on prices or loading factors (Bertrand, 1883; Mas-Colell, 1995). The default assumption is that $\dot{PL}_{c,t}$ is set equal to 0, because with homogenous insurers Bertrand competition results in a perfectly competitive market. It is assumed that reinsurance markets are dominated by a smaller number of firms, allowing for $\ddot{PL}_{c,t} = 0.5$ [7].

The value of $C_{c,t}$ is displayed in eq. (6.7), in which the cost of providing insurance is a fixed percentage of the insurance premium.

$$C_{c,t} = \frac{Operating\ costs_{c,t}}{Total\ premiums_{c,t}} \quad (6.7)$$

To arrive at a cost function for each national insurance industry, data from the OECD (OECD, 2015) insurance statistics database regarding the total value of gross premiums collected by the insurance industry and the total gross operating expenses for the years 2004–2014 for non-life insurance is used.

Eq. (6.8) is the econometric model used to estimate eq. (6.7). Eq. (6.8) is a multi-level hierarchical model, where the parameters of interest to vary over countries. A hierarchical model is estimated; as such a model uses the pan-national sample to estimate country specific parameters. This is important, as otherwise each country would have 10 observations. In eq. (6.8) β_1 and β_2 are estimated parameters which are constant across countries, $\dot{\mu}_{c,1}$ and $\dot{\mu}_{c,2}$ are estimated random effects parameters that vary across countries,$T_{c,t}$ is the time trend, ln represents the natural logarithm of the cost ratio in order to prevent estimated values of $C_{c,t}$ from becoming negative, and $\dot{e}_{c,t}$ is the error term:

[6] Eurostat variable: ilc_di03

[7] This loading factor is based on the values presented in Pakdel-Lashiji et al. (2015) and is adjusted by exceedance-probability.

$$Ln(C_{c,t}) = \beta_1 + \dot{\mu}_{c,1} + (\beta_2 + \dot{\mu}_{c,2})T_{c,t} + \dot{e}_{c,t} \quad (6.8)$$

A country-specific equation is the sum of the two sets of parameters. The estimated surcharges per country are shown in Table 6.3. Table 6.3 shows that, on the whole, across the EU countries there is a long-run trend of a falling ratio of operating costs to premiums, indicating increasing efficiency in the industry, which corresponds to an approximately 5% fall every year, on average, across the countries. However, the standard deviations of the random effect estimate for the time trend are quite wide, indicating that national contexts are quite different. The time trend results in two roughly equally sized groups of countries: those where cost loadings are increasing and those where cost loadings are falling. The group with falling costs tends towards a cost loading factor of about 2% of premiums by 2055, while the group with increasing costs tends towards a loading factor of about 25% by 2055. National loading factors are assumed to equal the sample average if national data are missing.

6.2.2.3 Insurance incentives for risk reduction (premium discounts)

Two risk reduction measures are focused upon: wet flood-proofing and dry flood-proofing buildings. Wet flood-proofing measures aim to limit the damage once water has entered a building, while dry flood-proofing aims to limit damage by preventing water from entering a building.

Chapter 5 developed an effectiveness indicator for wet and dry flood-proofing, shown in Table 5.2 which is again used in this chapter. The maximum degree of risk reduction is 37.4% if households employ both wet and dry flood-proofing measures. The possible premium discounts are shown in eq. (6.9) as the percentage by which the initially offered premium is lowered. The total discount of 34.7% is close to the risk modelling results of Poussin et al. (2012), whose methodology estimated that wet and dry flood-proofing retrofits of buildings can reduce flood risk by 40%–45%.

$$ER_{DRR} = \begin{cases} 0.128 & if \quad DRR = dry\,flood-proofing \\ 0.246 & if \quad DRR = wet\,flood-proofing \\ 0.347 & if \quad DRR = both\,flood-proofing \end{cases} \quad (6.9)$$

The households who implement these measures face lower premiums. The set of possible discounts assumes that the effectiveness of one measure does not alter the effectiveness of the other, because the measures focus on different aspects of protection.

Table 6.3 Estimated cost functions and cost surcharges

	Insurer cost behaviour		
	Baseline cost function		
	Constant	Time trend	
Fixed effects	-1.5 (0.093)	-0.071 (0.032)	
Random effect (standard deviation)	0.09 (0.027)	0.25 (0.084)	
N	122		
	Estimated surcharge as a percentage of the premium		
	2015	2035	2055
Austria	0.03	0	0
Belgium	0.15	0.03	0.01
Germany	0.05	0	0
Denmark	0.16	0.06	0.02
France	0.23	0.14	0.09
Spain	0.17	0.01	0
Finland	0.18	0.14	0.09
Ireland	0.1	0.01	0
Italy	0.26	0.2	0.15
The Netherlands	0.23	0.0	0.02
Sweden	0.15	0.05	0.02
The United Kingdom	0.11	0.02	0
Bulgaria	0.28	0.28	0.36
Czech Republic	0.14	0.02	0
Estonia	0.28	0.28	0.362
Greece	0.25	0.03	0
Croatia	0.28	0.28	0.36
Hungary	0.35	0.49	0.7
Lithuania	0.28	0.276	0.362
Luxembourg	0.16	0.07	0.04
Latvia	0.28	0.28	0.36
Poland	0.31	0.3	0.29

Portugal	0.25	0.19	0.14
Romania	0.28	0.28	0.36
Slovenia	0.28	0.28	0.36
Slovakia	0.35	0.54	0.82

6.2.2.4 Cost for low-risk households due to the level of risk sharing within a market structure

The insurance market structure can also place an additional cost on the households with low flood risk through the introduction of an explicit premium cross-subsidy between households. Such a subsidy requires some of the cost of households with high flood risk to be borne by households with low flood risk. This is viewed as a societal cost, since it forces low-risk households to pay larger insurance premiums for no return of insurance coverage (Penning-Rowsell and Pardoe, 2012). Low-risk households are defined as those with a flood probability that is lower than 1% per year (in the absence of protection standards). The cost for low-risk households, in total across the low-risk population, is presented in eq. (6.10). It is measured as the difference between the premiums that the insurance company collects from the high flood-risk households compared to the total expected damage to high-risk households in terms of net present value (NPV). Annual values are discounted at a rate of 3.5%.

$$Cost_{low\ risk\ households_{j,t}} = \sum_0^{20} \left(\frac{1}{1+0.035}\right)^t \left(\sum_i E\left(\bar{L}_{i,j,t}(p) - \bar{D}_{i,j,t}(p)\right) - \pi_{i,j,t,s}\right) \qquad (6.10)$$

In other words, the cost for low-risk households is the NPV of the subsidy that high-risk households receive from lower risk households. This subsidy is provided through a surcharge on the insurance policies of the low-risk households, for which they gain no direct benefit.

6.2.3 Model of household insurance demand and risk reduction behaviour

6.2.3.1 Flood insurance demand

Based on a review of the Wharton Risk Management and Decision Processes Center (2016); Paudel et al. (2012), Maccaferri et al. (2012), CCS (2008), Surminski and Eldridge (2015), and Lamond and Penning-Rowsell (2014), among others, the following assumptions regarding the flood insurance penetration rate in non-voluntary flood insurance markets are made. The solidarity market structure is assumed to have a penetration rate of 100% due to the formal legal mandate to buy flood coverage. The penetration rate of the semi-voluntary market is assumed to be 75%, while this value for the PPP market is assumed to be 85%, since PPP premiums are lower, thus inducing more low-income households to buy insurance. The semi-voluntary and PPP markets have a lower than 100% coverage rate even with a purchase requirement. The reasons are that building contents are less often insured[8] and many low-income households may not insure (Surminski and Eldridge, 2015). Moreover, in these markets, flood coverage is an informal rather than a formal requirement, so not all households buy insurance.

The household behaviour model consists of two elements. The first element applies only to the voluntary market structure, in which households have the choice of buying insurance. It is assumed that households will buy insurance if it is both utility maximizing and affordable in a subjective expected utility framework (Savage, 1954), which is a standard economic model of individual decision making under risk. In eq. (6.11), the new terms are $W_{i,j,t}$, which is the estimated wealth of a household in region j at time t[9] and α_i, which is the risk aversion of a household and is set at α_i=1, resulting in a log utility function. Subjective flood perceptions are introduced by assuming that

[8] The underlying risk model does not strongly differentiate between building and contents damage, which is why demand is also not explicitly distinguish between demand for insurance against these damage categories.

[9] Wealth is estimated by assuming it is a fixed proportion of income as indicated by: http://ec.europa.eu/eurostat/documents/3433488/5565228/KS-SF-10-033-EN.PDF/9b1042cd-4f2d-4984-9afe-aef8e5be3a5c?version=1.0; missing observations are set equal the sample average of 2.27 times income. Assuming a fixed ratio may underestimate the wealth of some households, thereby indicating that flood losses are more important than they are for a given level of wealth. This, however, produces an optimistic estimate of insurance penetration rates.

households consider losses over the probability range $[0,\widetilde{PS}_{i,j}]$, where $\widetilde{PS}_{i,j} = \vartheta_{i,j} PS_j$; and $\gamma_{i,j}$which is the perceived flood impact.

In eq. (6.11) the first element calculates the subjective expected utility of not being insured, that is, uncompensated flood losses. The second element presents the subjective expected utility of being insured. In that case the agent can only suffer a loss equal to the insurance deductible.

$$E(U) = \begin{cases} E(U_{1,i,j,t,s}) = \int_0^{p=\widetilde{PS}_{i,j}} pln(W_{i,j,t} - \gamma_{i,j} L_{i,j,t}(p))\, dp \\ E(\, U_{2,i,j,t,s}) = \int_0^{p=\widetilde{PS}_{i,j}} pln(W_{i,j,t} - 0.15\gamma_{i,j} L_{i,j,t}(p) - \pi_{i,j,t,s})dp \end{cases} \quad (6.11)$$

A potential policyholder will select the element of eq. (6.11) that provides the highest expected utility, subject to meeting the budget constraint. An important input for calculating eq. (6.11) is a distribution of individual flood perceptions. In order to generate a probability density function, information on subjective occurrence probabilities is required for $\vartheta_{i,j}$. The data used to generate this distribution is taken from Botzen et al. (2009, 2015). These studies investigated how perceptions of flood probabilities of households compare with objective flooding probabilities for a Dutch and New York sample, respectively. It was found that the data follows a Generalized Pareto distribution[10], as judged by Bayesian information criteria.

The PDF of the Generalized Pareto distribution of subjective occurrence probabilities, $[f(\vartheta_{i,j}|k,\sigma,\theta)]$, is given by eq. (6.12) and the calibrated parameters are shown in Table 6.4.

$$f(\vartheta_{i,j}|k,\sigma,\theta) = \left(\frac{1}{\sigma}\right)\left(1 + k\frac{\vartheta-\theta}{\sigma}\right)^{-\frac{1}{k}} \quad (6.12)$$

The fitted Generalized Pareto distributions must be calibrated to national contexts. This is done by following the approach developed in Chapter 5 in which deviations in subjective flood occurrence probabilities are related to the protection standards currently in place. It is assumed that the required Generalized Pareto distribution can be linearly interpolated based on the distribution estimated from the data presented in Botzen et al. (2009, 2015). In most cases, only the top 3% of values of the above distributions create a probability range outside of [0,1]. In order to correct for this, the above distributions is produced and then 10,000 values are drawn from the domain $[0, 1/PS_j]$. This is done because $\widetilde{PS}_{i,j}$ must have a maximum value of 1 to match the exceedance-probability curve.

A similar distribution must be calibrated for $\gamma_{i,j}$. A Generalized Pareto distribution is selected and calibrated based on data for Germany from GDV (2013). A report from the German Insurance Association states that the flood insurance penetration rate for German households was 33% for buildings and 19% for contents in 2013 (GDV, 2013). The Generalized Pareto distribution is calibrated such that the DIFI model produces an average penetration rate of 26% for Germany in 2015 under the private voluntary market structure. The calibrated distribution is then equally applied to other countries within the sample due to problems of data availability or the presence of a counterfactual situation (for example, France).

The budget constraint for eq. (6.11) is considered to be whether the insurance is affordable or not (given possible expenditure on risk reduction measures). If all or a proportion of the insurance premium is deemed to be unaffordable, then the household will not buy the insurance policy. Affordability is measured based on a method constructed in Chapter 5, which is derived from equity concerns. This definition is that an item of expenditure is unaffordable for a household if the money to be spent is larger than the household's poverty-adjusted disposable income (i.e. disposable income above the relative poverty line). The constraint presented in eq. (6.13) shows this

[10] The approach taken follows Chapter 5 whereby the desirability of the following distributions was tested against one another: Exponential, Extreme Value, Generalized Extreme Value, Generalized Pareto, Logistic, Normal, T-location scale.

mathematically as: $Income_{i,j,t}$ being the household's income and the poverty line being taken as the national poverty line (i.e. 60% of national median income). The magnitude of unaffordability for insurance premiums is estimated by the total sum of the unaffordable portion of an insurance premium within a given year.

The expression in eq. (6.13) summarizes the decision process of the households. Households will insure if it is both subjectively utility maximizing and affordable.

$$U = \begin{cases} insure \quad if \quad E(U)_{1,i,j,t,s} < E(U)_{2,i,j,t,s} \quad s.t. \pi_{i,j,t,s} \leq Income_{i,j,t} - Poverty\ Line_{c,t} \\ not\ insure \quad if \quad E(U)_{1,i,j,t,s} \geq E(U)_{2,i,j,t,s} \quad or \pi_{i,j,t,s} > \text{Income}_{i,j,t} - Poverty\ Line_{c,t} \end{cases} \tag{6.13}$$

Income for each household within each NUTS 2 region is drawn from a log-normal distribution, as is common. Wealth is assumed to be a fixed ratio of income taken from Eurostat. The log-normal distribution is calibrated to NUTS 2 data on mean and median income levels[11].

Table 6.4 Calibrated parameters of the distributions of flood occurrence perceptions

		Parameter estimates	
	K	σ	θ
		Subjective flood probabilities	
Austria	1.89	0.32	0
Belgium	1.91	0.29	0
Germany	1.85	0.41	0
Denmark	1.64	1.31	0
France	1.66	1.21	0
Spain	1.74	0.75	0
Finland	1.86	0.38	0
Ireland	1.76	0.64	0
Italy	1.82	0.47	0
The Netherlands	2.04	0.15	0
Sweden	1.66	1.16	0
The United Kingdom	1.9	0.31	0
Bulgaria	1.77	0.7	0
Czech Republic	1.8	0.64	0
Estonia	1.77	0.72	0
Greece	1.76	0.72	0
Croatia	1.76	0.73	0
Hungary	1.8	0.65	0

[11] The log-normal distribution only has two key parameters to be estimated, which are contained in the function for the mean and median values that can be found in Eurostat variables: nama_10r_2hhinc and nasa_10_ki

Lithuania	1.77	0.71	0
Luxembourg	1.8	0.64	0
Latvia	1.78	0.69	0
Poland	1.78	0.69	0
Portugal	1.76	0.73	0
Romania	1.78	0.69	0
Slovenia	1.79	0.66	0
Slovakia	1.8	0.64	0
Subjective flood impacts	-0.2	1	0.1

6.2.3.2 Employment of risk reduction measures

The second element of household behaviour that is modelled is the decision to invest in flood risk reduction measures. The approach taken is based upon Chapter 5 and extended here to account for budget constraints. It is assumed that policyholders make investment decisions on the basis of costs and benefits, while the perceived benefits of mitigation can diverge from actual benefits due to over- or underestimating flood risk or the benefits of risk reduction measures[12]. While a measure may be cost-effective in the long run, a household is unlikely to employ such a measure when it is currently unaffordable.

The households are assumed to have the following choice set of risk reduction measures {Dry flood-proofing, Wet flood-proofing, Dry and Wet flood-proofing} matching the set of possible premium discounts (the same as Chapter 5). Households base their decision on the higher of the two incentives (subjective risk perceptions or objective risk incentives). The calibration process from Chapter 5 is again employed. This generates 3 scenarios based on Kreibich et al. (2005), Poussin et al. (2014) and Bubeck et al. (2012).

Once the potential benefits in each period have been calculated, the household will make the cost-effectiveness calculation in eq. (6.14), using the higher value benefit in eq. (6.13). This can be interpreted in the following manner: If a household underestimates the benefits from risk reducing measures, then the decision to invest in mitigation is determined by the premium discount. Households that have subjective benefits of mitigation that are larger than the premium discount base their decision to mitigate on their subjective risk reduction beliefs. In other words, those households that overestimate the benefits of risk reduction will employ risk reducing measures even if these measures are not objectively cost-effective. These households have an intrinsic motivation to implement risk reduction measures, which proves to be an important part of the decision-making process (Chapter 4).

$$\omega^*_{i,j,t} = \begin{cases} \omega^{Incentive}_{i,j,t,DRR} & if\ \omega^{Incentive}_{i,j,t,DRR} > \omega^{Subjective}_{i,j,t,DRR} \\ \omega^{Subjective}_{i,j,t,DRR} & if\ \omega^{Incentive}_{i,j,t,DRR} \leq \omega^{Subjective}_{i,j,t,DRR} \end{cases} \quad (6.13)$$

Once the benefit of mitigation in a time period has been decided upon, the overall investment decision framework is presented in eq. (6.14). In eq. (6.14), a household will decide to invest in a particular risk reduction measure if the discounted benefits over 20 years are larger than the upfront investment costs, IC_{DRR}. Discrete time discounting is used where the discount rate is given by δ.

$$uptake = \begin{cases} Yes \quad if\ \sum_0^{20} \left(\frac{1}{1+\delta}\right)^t \omega^*_{i,j,t} - IC_{DRR} \geq 0 \quad and \quad IC_{DRR} < Income_{i,j,t} - Poverty\ Line - \pi_{i,j,t} \\ No \qquad\qquad if\ \sum_0^{20} \left(\frac{1}{1+\delta}\right)^t \omega^*_{i,j,t} - IC_{DRR} < 0 \end{cases}$$

(6.14)

[12] Due to the data sources used it is impossible to disentangle separate sources of over- or underestimation.

$$IC_{DRR} = \begin{cases} €471 & if \quad DRR = dry\,flood - proofing \\ €2389 & if \quad DRR = wet\,flood - proofing \\ €2860 & if \quad DRR = both\,flood - proofing \end{cases}$$

The discount rate (δ) is fixed at 3.5%. Households will only consider benefits over a 20-year period (Kreibich et al., 2011). This can either be viewed as the assumed lifespan of the measures or as myopia.

The approach taken is based on that presented in Chapter 5, which calibrated a generalized Pareto distribution of subjective risk reduction perceptions based on the data about implementation of flood preparedness measures by households in flood-prone areas (Kreibich et al., 2005; Bubeck et al., 2012; Poussin et al., 2014). The calibration of the baseline risk reduction perceptions distributions is based on the average risk faced and flood-proofing employment rate in the NUTS 2 regions covered in these studies. The parameters of the calibrated distribution are then assumed to be fixed and are applied to the separate NUTS 2 regions using the risk for that specific region. Therefore, 3 subjective risk reduction perception scenarios are developed.

6.2.4 Multi-criteria analysis

The multi-criteria analysis (MCA) evaluation framework is based on the following key evaluation criteria of: the mean national insurance penetration rate, the mean incentivized risk reduction, the net present value of magnitude of unaffordability, and the net present value of the cost that risk sharing between low- and high-risk households places on low-risk households. The values estimated in step 4 of the DIFI model are aggregated over time by generating the NPV of the indicators for the periods 2015–2035 and 2035–2055. The insurance penetration rate is not converted into a NPV, but is the average penetration rate over the period. The MCA is conducted at the national rather than the NUTS 2 level. Finally, the criterion values are aggregated over the three flood risk perception scenarios by using the average criterion value across the three scenarios.

Once the DIFI model output has been aggregated across flood risk perception scenarios at the national level, the criteria are standardized within a country and a weighted sum is produced. The weighted sum provides a single aggregated holistic score across the four criteria for each investigated national market structure within a country. The penetration rate and incentivized risk reduction are deemed to be benefits, while unaffordability and the cost for low-risk households are deemed to be costs. This follows the public debate regarding how flood risk management should be conducted.

The evaluation criteria are standardized and ranked following eq. (6.15). ${S^1}_{c,s}$ is the score for market structure s in country c for the first period (or the second if ${S^2}_{c,s}$). The values for each indicator are standardized, since this allows the variables to have a common metric and to be weighted according to perceived importance (Janssen and Herwijnen, 2007)[13]. The standardization process bounds score values by 0 and 1.

$${S^1}_{c,s} = \frac{\sum_{n=1}^{n=11}\sum_{m=1}^{m=4}\omega_m^n MCA_{j,t,s}}{11}, \quad where\ MCA_{m,j,t,s} = \begin{cases} \frac{A_{c,s}^1 - A_{c,s}^{1,Min}}{A_{c,s}^{1,Max} - A_{c,s}^{1,Min}} & if\ a\ benefit \\ 1 - \frac{A_{m,j,t,s}^1 - A_{m,j,t,s}^{1,Min}}{A_{c,s}^{1,Max} - A_{c,s}^{1,Min}} & if\ a\ cost \end{cases} \quad (6.15)$$

The possible choices for $\{\omega_m^n\}$ can alter the overall attractiveness of the various market structures for each country. To account for this potential effect, multiple sets of weights are used: (a) equal weights, where ω=1/4; (b) one element is weighted at ω=2/5 and the remaining two elements at ω=1/5 (with an alternating element with the double weight); and (c) two elements are weighted at ω=3/10 and the remaining elements at ω=1/5 (with alternating elements with the higher weight). There are 11 unique combinations of weights. It is quite likely that the overall MCA score will be sensitive to changes in the weights used and, because there is no clear guidance from stakeholders to set weights at the European level, the ranking of insurance market structures is based upon the

[13] While the mean score is presented in eq. (6.15) as the final indicator, using the median score does not produce noticeable differences.

mean aggregated score across the various sets of weights. It is left to future research to determine the weights that are applicable to specific locations to better tailor the presented framework.

6.3 Results

6.3.1 Optimal flood insurance market structures for the future

Figures 6.2A and 6.2B show how preferred market structures would evolve, towards the period 2035–2055, from the current situation to optimal structures. The optimal market structures per country are based on the aggregated MCA scores (0–1) reaching the best trade-off between economic efficiency and equity for the time periods 2015–2035 and 2035–2055.

The semi-voluntary PPP market (M4) is predicted to be optimal most often in the period 2015–2035 (70%) followed by the PPP market (M6), at 27%. In the period 2035–2055, the PPP (M6) is found most often to be the optimal structure (54%) followed by the semi-voluntary PPP (M4), at 38%. These two market structures display similar features, since the PPP market is an extended version of the semi-voluntary PPP market, as described in Table 6.2.

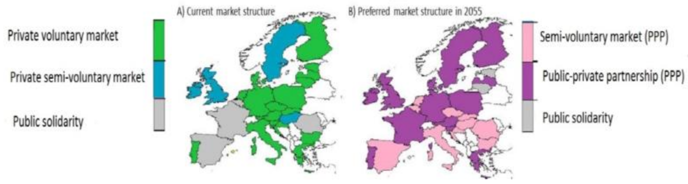

Figure 6.2 Market structure reforms suggested by the DIFI model results for the period 2035-2055

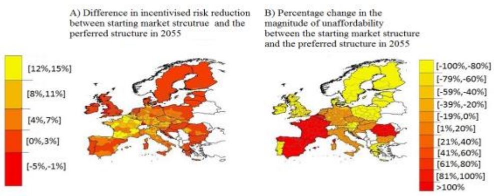

Figure 6.3 Example consequences of the insurance market reforms suggested by the DIFI model results for the period 2035-2055

The use of government-provided reinsurance in both structures improves affordability. The PPP market imposes lower costs on the low-risk households than would occur under a solidarity market structure, due to a smaller degree of premium cross-subsidization. The PPP market manages to provide an acceptable trade-off between the unaffordability of risk-based premiums and the ability of such premiums to incentivize policyholders to employ more risk reduction measures.

On the whole, Figure 6.2 shows that moving towards the modelled structures, based on varying degrees of public-private partnerships would result in an improvement in the amount of risk reduction undertaken by households across most modelled market structures (Figure 6.3) at the national level. The benefits of risk reduction increase over time due to increasing flood risk, which creates stronger incentives for households to implement risk reduction measures, especially when premiums are at least partly risk-based.

However, for the current solidarity market structures in some countries (e.g., France), the reform towards increased risk reduction incentives comes at the expense of affordability of insurance for those at highest risk, while reducing the premium costs for those households with lower risk (Figure 6.3). In contrast, for the current private market insurance, the unaffordability of insurance outweighs the potential risk reduction incentive of the insurance premiums, which implies reform towards PPP. While the introduction of a public reinsurer is desirable for all countries in the period

2015–2035, for a third of the EU countries it is desirable to strengthen the reforms by moving towards the PPP market in the next period 2035–2055.

6.3.2 Results for specific evaluation criteria

Overall, these findings support the call for households, the private sector, and the public sector to collaborate in a public-private partnership (e.g., Djalante et al., 2011) that balances the trade-offs between economic efficiency and equity. Without the proposed reforms, flood insurance premiums are predicted to grow rapidly and become unaffordable for many households. As an illustration, the DIFI model estimates that the average household premium (across the EU) could increase by 100% by 2055 over 2015 if premiums are fully differentiated to risk levels faced by policyholders, or by 90% if premiums are shared equally over all households. If the high premiums result in unaffordability of coverage for low-income households, then the most financially vulnerable households will bear much of the consequences of a flood themselves, unlike their more affluent counterparts.

Not directly presented in Figure 6.2 or Figure 6.3 is that the average household insurance premiums are lowest in the solidarity public structure (€5–€125 per year in 2015) and highest in the private voluntary markets (€30–€2000 per year in 2015). Premiums fall for higher degrees of cross-subsidization of premiums between high- and low-risk households. The magnitude of unaffordability follows a similar pattern because premiums are more likely to be unaffordable for low-income households in private voluntary markets where they are based on objective flood risk with little cross-subsidization. On average, across NUTS 2 regions, the voluntary private insurance premiums are unaffordable for about 21% of the regional population in high risk areas, while this is only the case for 16% in the PPP market. While with cross-subsidization the percentage of the population facing unaffordable insurance only falls by 5% (to 11%), the Net Present Value (NPV) associated with unaffordable premiums falls by 60% (SD=30%) on average. This implies that the PPP structure considerably decreases premium costs for low-income households.

However, the cost for low-risk households is lowest when premiums are based on risk. In that case, high-risk households must pay more of their expected loss themselves. For instance, under the voluntary market structures, the NPV of the direct subsidy between high- and low-risk households is €0, while under the solidarity structure in the Netherlands, the UK and Sweden, the NPV of this subsidy between 2015 and 2035 is predicted by the model to be roughly €300 million in total. This shows that increasing the degree of risk sharing may impose high costs on low-risk households for which they receive no direct benefits.

The modelled insurance penetration rates are stable over time, and the modelled voluntary private market penetration rates are about 75% lower than those for the markets with purchase requirements.
The insurance-based risk reduction incentives are not found to be effective in the solidarity public structure, because the premium discount that policyholders receive for implementing risk reduction measures is too low (an average of €14 per year in 2055).

The PPP markets are found to be more successful in incentivizing dry flood-proofing (measures aimed at preventing water from entering a building) because the annual financial incentive to implement those measures is nearly 4 times as large as in the solidarity public structures. These incentives in the PPP market are less effective in stimulating wet flood-proofing measures aimed at limiting damage once water has entered a building, due to their higher investment costs.

The modelled voluntary market structures offer stronger incentives in terms of premium discounts of, on average, €500 per year, which make flood-proofing measures cost effective for many households. However, fewer households are exposed to this incentive due to the lower market penetration rate of flood insurance. Moreover, while the high premium discounts for risk mitigation imply that insured households are more likely to find the measures cost-effective, the size of the premium may result in the household being unable to afford risk reduction measures.

The modelled optimal markets increase the degree of risk reduction by an average of an additional 7 percentage points across NUTS 2 regions in 2055 compared to the original market structures.

6.3.3 Sensitivity analysis

6.3.3.1 Uncertainty in risk and insurance premium estimates

An important source of uncertainty in this study is the estimated insurance premium, as the value of the premium is a major driving force behind the market rankings. Therefore, this section examines the sensitivity of this chapter's main results to two sources of uncertainty in the premium; namely, (1) uncertainty of the underlying aggregate risk estimate and (2) uncertainty of the number of households in a high-risk flood zone at a certain point in time. It should be realized that the effects of including cost and profit loadings emanate from the underlying risk estimate, which is why the risk estimate is central to this sensitivity analysis.

The influence of uncertainty on the underlying risk estimate is examined by estimating the 95% confidence interval around the estimated probability exceedance curves used to calculate the expected annual damage. The upper and lower bounds of the damage estimates result in the estimated premiums being, on average, 4% higher or lower, respectively, across the EU countries over the entire period. Countries located in Western Europe are closer to a change of 1%, while those in Eastern Europe are closer to a change of 5%. The second source of uncertainty in premiums is the fact that the number of households is different per market structure. The solidarity market structure uses official Eurostat estimates for the number of households within a country and, thus, has little uncertainty. The remaining market structures require an estimation of the number of households in an area with high flood risk. The uncertainty in the number of households is measured by constructing a 95% confidence interval around the ratio of households to overall population. Using the upper limit (a smaller number of households) of this ratio increases the modelled premiums, while using the lower limit (a larger number of households) lowers average premiums. The effect of the uncertainty in the number of households has a larger effect on premiums than did estimates of the risk. Nevertheless, taking these sources of uncertainty into account (individually) results in the PPP and semi-voluntary market features remaining as the most commonly optimal market structure. The only noticeable difference is that, under the lower risk bounds for the period 2035–2055, the PPP market is the optimal market in slightly fewer countries.

6.3.3.2 Different flood risk scenarios

Instead of the current SSP scenarios of economic and population growth, the A1 climate projection can be combined with the SRES scenarios. Including the SRES scenarios produces a higher level of flood risk than the ensemble SSP scenarios used for the baseline results; in particular, flood risk is up to 17 times larger due to economic development alone under the SRES scenarios. The main influence of using the higher flood risk projections based on SRES is that the PPP market becomes optimal for almost all countries, because of its ability to provide strong risk reduction incentives. This strengthens this chapter's baseline findings about the desirability of the PPP market.

6.3.3.3 Alternate construction of the insurance premium discount

Our initial analysis assumed that any risk reduction measure employed would lower the premium offered by the insurance sector. However, in the PPP and solidarity markets, the premium offered to a household does not fully reflect their risk. Therefore, an alternative premium discount for risk reduction could be that premiums are only lowered if, for example, element 1 of eq. (6.4) is reduced to a level below element 2 of eq. (6.4) In effect, altering this assumption removes the household-level reward for risk reduction and prevents the employment of additional risk reduction measures in the PPP market structure. Altering this assumption renders the semi-voluntary market most commonly optimal. However, as mentioned in the main part of the chapter, the semi-voluntary and PPP market structures have quite similar features overall.

6.3.3.4 Using a single national pool of high-risk households rather than regional differentiation

Instead of basing the model on separate insurance premiums at the NUTS 2 level premiums can also be based on a single pool of all NUTS 2 regions at the national level. This change would increase the degree of solidarity between households within the high-risk flood-plain. The main result of this alteration is that the semi-voluntary structure (PPP) becomes more often the optimal structure in the first period. However, in the second period the results are quite consistent between using separate regional pools or a single national pool. Overall, this change in geographical detail can result in a slightly different ranking for some countries, but the main conclusions regarding the most desirable market features remain the same.

6.3.3.5 Alternative assumptions about the costs and effectiveness of risk reduction measures

Here we examine the sensitivity of this chapter's main results to different assumptions about the costs and effectiveness of risk reduction measures, which can affect the estimated employment of these measures by households and the incentivized risk reduction by insurance. This is done by running the model with the upper and low bounds of the cost estimates for both dry and wet flood-proofing reported in Chapter 5. These results show that deviating from the baseline cost estimates does not change the impact of the risk reduction incentives for the solidarity insurance market structure. This is the case because the NPV of the premium discounts is too small, regardless of the costs, to influence decisions to take these measures. The results for the voluntary market structures and the PPP market structure show that using the lower bound of the cost estimates increases the average amount of risk reduction occurring, while using the higher bound of costs lowers the total risk reduction. However, the overall ranking of insurance market structures is robust to using the upper cost estimate.

Apart from flood-proofing costs, there is the possibility that when a household employs both dry and wet flood-proofing measures, the two can interact with each other and reduce total effectiveness of these measures. This in turn can limit the incentive to take both measures. The two measures are in effect sequential, in that dry flood-proofing aims at preventing water from entering a building and then wet flood-proofing mitigates damage of water that still enters. In this sensitivity test, it is assumed that dry flood-proofing remains as effective as stated above, while the effectiveness of wet flood-proofing is reduced to 21%, to take into account that it offers less protection after dry flood-proofing is implemented. The results show that this change has no noticeable influence on flood-proofing decisions.

6.3.3.6 Alternative assumptions on the utility function determining flood insurance demand Alternate decision theory

There is a debate in the literature regarding how households behave when faced with low-probability/high-impact events and the behavioural heuristics involved (Starmer, 2000). There are a range of behavioural rules that have been proposed as alternatives to the subjective expected utility theory used to model individual flood insurance purchases for this chapter's main results. This section investigates how sensitive this chapter's main findings are to using a different behavioural decision rule, namely prospect theory which is the main alternative theory that has been proposed to model individual decision making under low-probability/high-impact risk (Botzen and van den Bergh, 2009).

The utility function of prospect theory deviates from that of standard expected utility theory in that losses or gains are valued as deviations from a reference level of wealth. Additionally, prospect theory employs a probability weighting function where events with a higher exceedance-probability receive a lower weight compared to expected utility, while low exceedance-probability events are overweighed (Tversky and Kahneman, 1992). The general utility function of prospect theory is:

$$E\big(U(x)\big) = \int \frac{p_i^{\delta}}{\left(p_i^{\delta}+(1-p_i)^{\delta}\right)^{\frac{1}{\delta}}}\left(-\lambda(-x)^{\theta}\right)dp_i \qquad (6.16)$$

In the above equation, λ is a loss-aversion parameter. The parameter θ reflects Constant Relative Risk Aversion and δ is the curvature of the probability weighting function. Overall, using prospect theory alters both the insurance penetration rate in voluntary and semi-voluntary flood insurance markets and the incentivized risk reduction.

Alternate functional form of the utility function

Moreover, the results may be sensitive to the nature of the utility function as several approaches have been taken (see Haer et al., 2016 for an example):

$$E(U) = \begin{cases} E\left(U_{1,i,j,t,s}\right) = \int_0^{p=\widetilde{PS}_j} p\,\frac{(W_{i,j,t}-\gamma_{i,j}L_{j,t}(p))^{1-\theta}}{1-\theta}\,dp \\ E\left(U_{2,i,j,t,s}\right) = \int_0^{p=\widetilde{PS}_j} p\,\frac{(W_{i,j,t}-0.15\gamma_{i,j}L_{j,t}(p)-)^{1-\theta}}{1-\theta}\,dp \end{cases} \quad (6.17)$$

In eq. (6.17) θ is now assumed to be normally distributed with a mean equal to 1 and a standard deviation equal to 0.025. This distribution will produce many σ values close to 1 (and hence a logarithmic utility function) but some households will be more or less risk averse than others. Randomly drawn values equal to 1 are assumed to generate a logarithmic utility function.

Overall, the results of the sensitivity analyses with differing utility functions show that the ranking of insurance market structures remains very similar, with the PPP or the semi-voluntary (PPP) market structures being ranked the highest.

Altering flood occurrence perceptions

The sensitivity of the results to the flood occurrence perception distribution is tested by altering eq. (6.12) in two ways. The first is by setting $\gamma_{i,j}$ equal to 1. In doing so, the average penetration rates double on average for the two voluntary markets, but now a greater number of households find the risk reduction measures unaffordable. This has the effect of increasing the number of markets where a PPP structure is optimal by three by 2035–2055, although the optimality of most markets remained the same as shown in Figure 6.2. The second is by using the objective rather than subjective flood probabilities. The difference in estimated penetration rates is thus smaller on the whole, resulting in no noticeable differences in the final optimal market for each country.

6.3.3.7 Continuous MCA ranking

The primary MCA evaluation method was based on ordinal scores. However, this section examines the sensitivity of the results to using a continuous score, as shown in eq. (6.18).

$$MCA_{m,j,\mathrm{t,s}} = \begin{cases} \frac{\mathrm{A_{m,j,t,s}}}{\mathrm{A^{Max}_{m,j,t,s}}} & \text{if a benefit} \\ 1-\frac{\mathrm{A_{m,j,t,s}}}{\mathrm{A^{Max}_{m,j,t,s}}} & \text{if a cost} \end{cases} \quad (6.18)$$

While this changes the value of the scores, the overall rankings of the market structures do not differ from the MCA with the ordinal ranking.

Moreover, the baseline results used 11 sets of weights and compressed them into an overall score. If instead, 24 and 35 unique sets of weights are used then no noticeable influence is observed on how the market structures are ranked.

6.4 Discussion and conclusion

To this chapter's knowledge, this is the first large-scale study that integrates flood risk assessment, the insurance sector, and consumer behaviour in one modelling approach to assess insurance market structures against increasing flood risk under climate change. The DIFI model estimates that on average risk-based insurance premiums could double for the countries investigated between 2015 and 2055 if no flood insurance market reforms are undertaken. Hence, increasing flood risk will place pressures on stakeholders, such as insurers, to meet international agreements on disaster risk reduction, such as the Hyogo and the Sendai frameworks (Wilby and Keenan, 2012; UNISDR, 2015; Mysiak et al., 2016). Insurance could play an important role in both providing financial protection against flood losses and incentives for risk reduction and adaptation to climate change. Flood insurance arrangements require reform to cope with increasing risk, and this chapter demonstrates that household-level risk reduction measures can be incentivized through a stronger link between risk reduction and the premiums charged (Kunreuther, 1996; Michel-Kerjan, 2010).

By 2055, the PPP market was found to be the most desirable set of market features for most countries in the future to cope with climate change, followed by the semi-voluntary market supported by a public reinsurer. The most promising market structures displayed similar features: a public reinsurer and a limited degree of sharing of losses between high and low-risk households, a strong link between premiums and risk reduction, and insurance purchase requirements. These features maintain insurance affordability while providing sufficient incentives for risk reduction to encourage adaptation to changing flood risk.

Several studies argue that there is no one-size-fits-all solution for natural disaster insurance markets (Surminski et al., 2016). An example is the public response to the EC green paper on disaster insurance, which showed that many of the respondents were against the harmonization of insurance regulations across the European Union (Surminski et al., 2015). This chapter's focus, however, is on deriving general characteristics to guide reforms, and there are still many options for fine-tuning the exact method of implementation. Moreover, there is not a single optimal market structure across periods and countries. Instead this chapter finds that a process of continued reform over time is advisable for most of Europe: from the current market structure to the semi-voluntary PPP market and then to the PPP market.

This chapter finds that unaffordability remains a concern even in the solidarity market structure where the link between insurance and risk is weakest. This suggests that this general problem arises in all the market structures considered here. Overcoming problems with unaffordability may require the use of public policies (such as insurance vouchers), as has been proposed by Kousky and Kunreuther (2014). An insurance voucher is provided by the government to low-income households for the proportion of the insurance premium deemed to be unaffordable. The vouchers are issued on a temporary basis to smooth the transition to new market structures. While vouchers can ease the cost that high premiums place on low-income households, the vouchers should remain temporary to prevent an implicit subsidy for development in flood-prone areas (Kousky and Kunreuther, 2014).

Another way to improve affordability is the increased sharing of losses over many policyholders through the introduction of purchase requirements. Introducing requirements to purchase flood insurance creates a large pool of insured households, which lowers premiums, even in the absence of substantial cross subsidization of premiums between low- and high-risk households as implied by the solidarity structure. Moreover, purchase requirements limit the ability of asymmetric information to cause market failures through adverse selection.

However, the introduction of requirements may also be politically difficult, because it can be seen to limit consumer freedom. This is shown by discussions regarding insurance reforms in the Netherlands (Botzen, 2013) and Germany (CCS, 2008).

The use of public reinsurance can also limit insurance premiums and, thereby, partly overcome problems with coverage unaffordability. This chapter's evaluation over time shows that this is especially attractive when flood risks increase. Risk-averse insurers increase their premiums when low-probability/high-impact risks increase, especially when these risks are uncertain (Kunreuther and Michel-Kerjan, 2011), as is the case with flood risk in a changing climate (IPCC, 2012). It may be argued that governments can more cheaply reinsure extreme losses (Cardenas et al., 2007), because

European governments are, for the most part, risk neutral. Moreover, this chapter finds that a public reinsurance facility does not interfere too strongly with the underlying risk signal and incentives for risk reduction. This is the case because primary insurers pay for the government support they receive though risk-based reinsurance premiums and this reinsurance premium is, in the end, reflected in the premium that households pay. Another advantage of this payment structure is that the government (and thereby tax payers overall) receives a fair share of compensation for provided reinsurance.

Our findings have policy relevance for specific European countries. There is some similarity between the PPP market and the UK's recently introduced Flood Re. Both are based on the mandated purchase of insurance through mortgage conditions with an explicit subsidy for high-risk households. However, this chapter finds that the current structure of Flood Re is not optimal for the UK since incentives for risk reduction are absent.

The solidarity-based market structures of Belgium, France and Spain are also in need of reforms. The reason is that their current market structures may not be suitable for coping with future increases in flood risk due to insufficient incentives for risk reduction. The current solidarity-based markets may be better served by stimulating risk reduction through risk-based premiums, while addressing equity concerns using additional public policies (e.g., means tested insurance vouchers). The remaining countries with a voluntary purchase requirement should consider promoting or strengthening purchase requirements, as otherwise the penetration rate remains low, preventing many of the benefits of insurance as a risk management tool from being realized. For instance, in Hungary, the insurance penetration rate has been increased through mortgage providers requiring flood insurance coverage for eligibility for a mortgage (Linnerooth-Bayer et al., 2013).

Our main policy recommendations may also be applicable outside of Europe. For instance, the National Flood Insurance Program (NFIP) in the U.S. has undergone many potential reforms such as the Biggert-Waters Flood Insurance Reform Act of 2012, the Homeowners Flood Insurance Affordability Act of 2014, and the Flood Insurance Market Parity and Modernization Act of 2016. These acts are aimed at improving the financial sustainability of the NFIP (FEMA, 2016). Moreover, these reforms aim to improve the actuarial soundness of the program by moving towards risk-based premiums, while strengthening purchase requirements to overcome the observed low penetration rate outside high-risk areas (Michel-Kerjan et al., 2015) and improving incentives for risk reduction. Michel-Kerjan and Kunreuther (2011) propose for the NFIP a set of reforms similar to those this chapter finds applicable for most European countries based on the DIFI model analysis.