Implications of Multiple Curve Construction in the Swedish Swap Market

ERIK LIDHOLM
BENJAMIN NUDEL

KTH Industrial Engineering and Management

Master of Science Thesis
Stockholm, Sweden 2014

Implikationer från Skapande av Multipla Kurvor på den Svenska Swapmarknaden

ERIK LIDHOLM
BENJAMIN NUDEL

KTH Industriell teknik och management

Examensarbete
Stockholm, Sverige 2014

Implications of Multiple Curve Construction in the Swedish Swap Market

Erik Lidholm
Benjamin Nudel

Master of Science Thesis INDEK 2014:46
KTH Industrial Engineering and Management
Industrial Management
SE-100 44 STOCKHOLM

Implikationer från Skapande av Multipla Kurvor på den Svenska Swapmarknaden

Erik Lidholm
Benjamin Nudel

Examensarbete INDEK 2014:46
KTH Industriell teknik och management
Industriell ekonomi och organisation
SE-100 44 STOCKHOLM

KTH Industrial Engineering and Management

Master of Science Thesis INDEK 2014:46

Implications of Multiple Curve Construction in the Swedish Swap Market

Erik Lidholm
Benjamin Nudel

Approved	Examiner	Supervisor
2014-06-04	Hans Lööf	Tomas Sörensson
	Commissioner	Contact Person
	-	-

Abstract

The global financial crisis of 2007 caused abrupt changes in the financial markets. Interest rates that were known to follow each other diverged. Furthermore, both regulation and an increased awareness of counterparty credit risks have fuelled a growth of collateralised contracts. As a consequence, pre-crisis swap pricing methods are no longer valid. In light of this, the purpose of this thesis is to apply a framework to the Swedish swap market that is able to consistently price interest rate and cross currency swaps in the presence of non-negligible cross currency basis spreads, and to investigate the pricing differences arising from the use and type of collateral. Through the implementation of a framework proposed by Fujii, Shimada and Takahashi (2010b), it is shown that the usage of collateral has a noticeable impact on the pricing. Ten year forward starting swaps are found to be priced at lower rates under collateral. Moreover, the results from pricing off-market swaps show that disregarding the impact of collateral would cause one to consistently underestimate the change in value of a contract, whether in or out of the money. The choice of collateral currency is also shown to matter, as pricing under SEK and USD as the collateral currencies yielded different results, in terms of constructed curves as well as in the pricing of spot starting, forward starting and off-market swaps. Based on the results from the pricing of off-market swaps, two scenarios are outlined that exemplify the importance of correct pricing methods when terminating and novating swaps. It is concluded that a market participant who fails to recognise the pricing implications from the usage and type of collateral could incur substantial losses.

Keywords: collateral, cross currency, discount curve, forward curve, forward starting, off-market, swap, Stibor

KTH Industriell teknik och management

Examensarbete INDEK 2014:46

Implikationer från Skapande av Multipla Kurvor på den Svenska Swapmarknaden

Erik Lidholm
Benjamin Nudel

Godkänt	Examinator	Handledare
2014-06-04	Hans Lööf	Tomas Sörensson
	Uppdragsgivare	Kontaktperson
	-	-

Sammanfattning

Finanskrisens utbrott år 2007 orsakade abrupta förändringar i finansmarknaden. Räntor som tidigare följt varandra divergerade. Vidare gav både reglering av finansmarknaden och en ökad medvetenhet om motparters kreditrisk upphov till en tillväxt av kontrakt med ställda säkerheter. Följaktligen är det inte längre korrekt att prissätta swappar enligt metoder från tiden före finanskrisen. Mot bakgrund av detta är syftet med denna uppsats att applicera ett ramverk på den svenska swapmarknaden som på ett konsekvent sätt kan prissätta ränte- och valutaswappar med icke negligerbara räntespreadar, samt att undersöka prisskillnaderna som uppstår från användandet och typen av ställda säkerheter. Genom implementering av ett ramverk av Fujii, Shimada och Takahashi (2010b) visar denna studie att användandet av ställda säkerheter har en noterbar påverkan på prissättningen. Swappar med tio års löptider och framtida startdatum prissattes lägre när ställda säkerheter inkluderades i prissättningen. Vidare visar resultaten från prissättningen av off-market swappar att genom att bortse från effekten av ställda säkerheter så undervärderas ett kontrakts värdeförändring genomgående, oavsett om kontraktet är in the money eller out of the money. Valet av valuta på de ställda säkerheterna visade sig också spela roll, då prissättningen med SEK och USD som säkerhetsvalutor gav olika resultat i termer av konstruerade kurvor och i prissättning av spot-startande, framtida startande och off-market swappar. Baserat på resultaten ovan genererades två scenarion som påvisade vikten av en korrekt prissättningsmetod vid byte av motpart eller stängning av en swap. Härifrån dras slutsatsen att en marknadsaktör som inte inser vilken påverkan valet av ställda säkerheter har på prissättningen kan drabbas av betydande förluster.

Nyckelord: collateral, cross currency, diskonteringskurva, forwardkurva, forward starting, off-market, swap, Stibor

Acknowledgements

We would like to thank Linus Kaisajuntti and Julien Warmberg for the introduction to the topic of this thesis. Furthermore, we would also like to express our gratitude to our supervisor Tomas Sörensson at KTH for the valuable input throughout the process. Lastly, we would like to thank our families and friends for the continuous support.

Stockholm, June 2014
Erik Lidholm & Benjamin Nudel

Table of Contents

List of Figures

List of Tables

List of Definitions

Collateral Assets posted or received in order to mitigate the counterparty credit risk of a contract.

Collateral Rate Interest rate received (paid) on posted (received) collateral.

Cross Currency Basis Spread The spread added to one of the parties of a cross currency swap to price the contract at par.

Cross Currency Swap (CCS) A contract between two parties to exchange interest rate payments and notional amounts from two different currencies.

Day Count Factor A ratio (number of interest bearing days of a period divided by the number of days of a full year) that describes how interest is accrued.

Deposit A zero coupon contract where one party pays a notional amount at the spot date to receive the notional plus interest at maturity.

Discount Curve Describes the discount factors for a continuous set of maturities.

Effective Federal Funds Rate An overnight interest rate that is calculated by the Federal Reserve Bank of New York as an average rate on trades arranged by large brokers.

Foreign Exchange Forward (FX Forward) A contract to exchange one currency for another at a future time.

Forward Curve Describes the forward rates for a continuous set of time points.

Forward Rate Agreement (FRA) A deposit agreed upon today and effective in the future.

Forward Starting Swap A swap agreed upon today with a future start date (after the spot date).

Interest Rate Swap (IRS) A contract between two parties to exchange fixed and floating interest rate payments based on a common notional amount.

Libor London Interbank Offered Rate, which is an average of the perceived costs for unsecured funding estimated for a number of London banks.

Novation The change of counterparty in a contract.

Off-market Swap A swap that is either in or out of the money.

Overnight Indexed Swap (OIS) A fixed for floating interest rate swap where the floating leg consists of a compounded overnight rate.

Stibor Stockholm Interbank Offered Rate, which is an average of the unsecured lending rate demanded by a panel of banks active on the Swedish market.

Stina Stibor Tomorrow Next Average, which is a SEK overnight interest rate.

Swap Rate The fixed rate of the interest rate swap that prices the contract at par.

Synthetic Instrument An instrument constructed from other market instruments through, for instance, interpolation.

Tenor Basis Spread The spread added to one of the parties of a tenor swap to price the contract at par.

Tenor Swap (TS) A contract between two parties to exchange interest rate amounts based on different floating reference rates.

Termination The closing of a contract.

1 Introduction

1.1 Background

The first swap was constructed in the early 1980s (Bicksler and Chen, 1986). Since then, swaps have become popular instruments and can be divided into three main types; the plain vanilla interest rate swap (IRS) where two parties exchange fixed and floating rate payments, the tenor swap (TS) where two parties exchange interest rate payments based on different floating reference rates and the cross currency swaps (CCS) where two parties exchange interest rate payments in two different currencies.

The rise in popularity of the swap can be motivated by a number of beneficial properties of the instrument. Broadly speaking, the interest rate swap allows companies and institutions to hedge their interest rate exposures. For instance, the contract can be beneficial for firms experiencing a mismatch between the rate sensitivity of its assets and liabilities (Avram, Beal, Gup, Kolari and Lambert, 2007). One example could be a mortgage institution funding its long term mortgages through short term funding, meaning that its liabilities suffer from a greater exposure to adverse changes in interest rates. By entering an interest rate swap contract as a fixed payer, such a firm can better match the rate sensitivity of its assets and liabilities. In other words, the swaps can be used to restructure the composition of a firm's debt, in order to attain a desired level of exposure (Bicksler and Chen, 1986). Moreover, the contract can also help firms to lower their funding costs (Bicksler and Chen, 1986; Hull, 2012). It could be the case that one firm desires a fixed rate funding but has a comparative advantage in the floating market, or vice versa. This firm can then borrow in the market where it possesses the comparative advantage and then transform the loan into the desired form by using an interest rate swap. The same kind of argument can be made with the domestic and foreign markets. Through the use of cross currency swaps, a firm can borrow in the market where it possesses its comparative advantage and then swap to the desired currency and rate type (Hull, 2012).

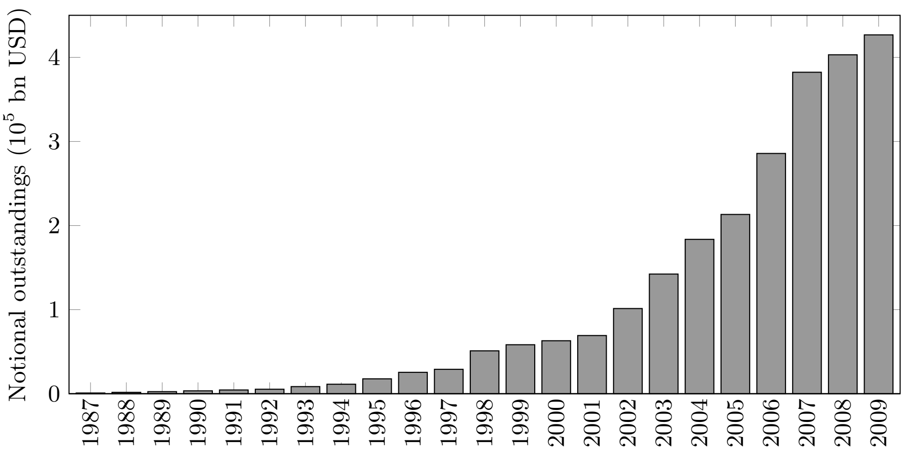


Figure 1.1: Growth of the Outstanding Notional of Currency and Interest Rate Contracts. (International Swaps and Derivatives Association, 2013)

Since the instrument first surfaced, the market has grown significantly. Looking at Fig. 1.1 which is based on data from ISDA (International Swaps and Derivatives Association), one can see that the outstanding notional in currency and interest rate contracts has grown significantly. More precisely, the outstanding notional of these contracts grew from 865.60 bn USD in 1987 to 426,749.60 bn USD in 2009 (International Swaps and Derivatives Association, 2010).

1.1.1 Pre-crisis Pricing

Historically, interest rate swaps have been priced in a so-called single curve framework, meaning that one unique yield curve have been used to extract the relevant discount factors and forward rates needed to derive the price. This textbook approach is exemplified in literature such as Hull (2012). One motivation behind this approach was the assumption of a unique risk free rate at which one could borrow and lend (Piterbarg, 2010). Furthermore, it was also assumed that interbank offered rates were risk free, and thus the matters of interbank illiquidity and credit issues were neglected (Ametrano and Bianchetti, 2013). Another important aspect was the fact that before the recent financial crisis erupted in 2007, practitioners neglected the small but present discrepancies that could be observed when comparing different interest rates benchmarks or tenors. For instance, two swaps with the same maturities linked to the same floating interest rate benchmark but with different tenors, say three months and six months respectively, would be assigned the same quotes. Another example of the small spreads inherent in the market at the time is found when looking at the spread between the Libor (London interbank offered rate) and OIS (Overnight Indexed Swap) rates. This spread was small enough for both of the benchmarks to be considered risk free, which reinforces the previously mentioned assumption that the interbank market was indeed assumed to be risk free. (Mercurio, 2009)

1.1.2 The Financial Crisis

As the financial crisis hit in August 2007, the market participants around the world witnessed an abrupt change in the money market conditions. Interest rate benchmarks such as the Libor rates soared, while the Feds effective funds rate deviated substantially from its target level. In order to control the overnight interest rate, the Fed pumped in liquidity in the market, but the efforts were to no avail. Not only did the interest rates rise but past relationships were also broken down and the Fed was not able to impose its target. The events outlined above were just the starting point of an extended period of market turmoil, with high and volatile spreads between overnight and longer term lending. (Taylor and Williams, 2009)

There have been discussions among both practitioners and academics about whether the Libor spreads were affected by counterparty risk or the lack of liquidity. Some argue that the spreads are represented well by liquidity issues (Ji and In, 2010). From a practitioner's point of view, the financial crisis induced a mismatch between supply and demand of liquidity. One could argue that the banks withdrew their liquidity from the market in order to cover their potential losses. Apart from the hoarding of funds to cover potential shortfalls, another explanation of the liquidity problem was that the banks needed liquidity to strengthen their balance sheets and financial reports (Ji and

In, 2010). In the turbulent times, where banks were under heavy scrutiny, it could be argued that banks were finding it important to show strength. Another way to explain the spreads is in terms of counterparty risk. Then, the assumption would not be that banks were reluctant to lend on the interbank market due to its own potential shortfalls, but rather due to the recent awareness of the fact that other banks could default. In times where several of the firms were writing down assets due to downgrades or defaults, one could view the market spreads as caused by a higher demanded risk premium. (Taylor and Williams, 2009)

1.1.3 Post-crisis Pricing

Before the recent financial crisis, the research regarding pricing of interest rate swaps and related topics was rather limited. Pricing was, as previously mentioned, done in a single curve environment. However, as pointed out by Bianchetti (2009) the meltdown caused by the financial crisis prompted quantitative researchers to reassess assumptions and pricing methods.

One aspect that the new pricing methods had to deal with was the deviation from previously negligible levels for both tenor and cross currency basis spreads, which are set to price the tenor and cross currency swaps at par. From now on, each floating rate tenor had to be assigned its own forward rate curve. This is the first part of the reason for the term multiple curve pricing, which surfaced after the crisis. Although the cross currency basis spreads were already present before the financial crisis, the importance of correctly pricing cross currency swaps has grown with the now larger spreads. The increase in the cross currency spreads is exemplified by Chibane, Selvaraj and Sheldon (2009).

Apart from the treatment of the now wider spreads, another area that has received attention is the discounting methods. As previously mentioned, the financial crisis surfaced questions on what is considered risk free. As explained by Wood (2009), the greater perception of counterparty credit risk has forced academics and practitioners to reassess the properties of interbank lending, implying that Libor can no longer be considered default free. This view is in line with that of Madigan (2008) who says that the new perception is justified through the now larger spread between Libor rates and the essentially risk free OIS rates, which historically was around 10-15 basis points. Since this spread could be said to measure the perceived liquidity and credit risk in the interbank market, this implies a higher degree of risk. Another aspect from which one can question the previous discounting methods is the rise in popularity among market participants to enter into collateral agreements. For example, over the term of the interest rate swap contract, the party experiencing a positive present value receives a matching collateral amount from the counterparty and pays a collateral rate based on the received amount. This kind of contract could be considered risk free (depending of course on the frequency of which one posts collateral) and thus the collateral rate is usually linked to the relevant overnight rate (Piterbarg, 2010). The change in discounting methods is the second factor resulting in the multiple curve pricing. The recent growth of collateralised agreements for non-cleared over the counter (OTC) transactions is illustrated in Fig. 1.2.

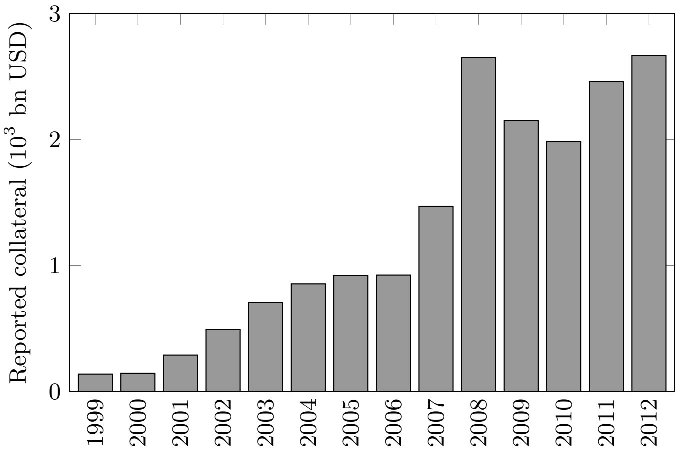


Figure 1.2: Estimated Growth of Reported Collateral of Non-cleared OTC Transactions. (International Swaps and Derivatives Association, 2010)

To summarise, when pricing a swap contract one now has to incorporate the relevant cross currency and tenor basis spreads as well as potential collateral agreements, which increases the complexity of implementing a swap pricing framework. The treatment of these spreads and the change in discounting methods is what causes the transition to a so-called multiple curve pricing method.

1.2 Problem Formulation, Purpose and Research Questions

Today it is a problem that pre-crisis pricing methods are no longer valid. Disregarding previously negligible tenor and cross currency basis spreads will result in a mispricing of swap contracts. Furthermore, increased usage of collateral due to regulations and awareness of counterparty credit risks also impact the pricing since it changes the discounting of future cash flows.

The purpose of this thesis is to apply a framework to the Swedish swap market that is able to consistently price interest rate and cross currency swaps in the presence of non-negligible cross currency basis spreads, and to investigate the pricing differences arising from the use and type of collateral. More precisely, the thesis aims to answer the following research questions:

- ◇ What is the mispricing effect for a swap market participant who adheres to pre-crisis instead of post-crisis frameworks? More specifically, what is the difference in terms of pricing with and without collateral?
- ◇ How does the choice of underlying collateral impact the pricing?
- ◇ How is the impact from the use and the type of collateral manifested when a swap contract is either novated or terminated?

In order to answer these questions, a pricing framework proposed by Fujii, Shimada and Takahashi (2010b) that takes both basis spreads and collateral into account will be implemented. This is done for SEK and USD swaps in order to show that it matters how one build the underlying curves and that the use and type of collateral can impact the pricing. In other words, these questions are answered for the Swedish market, where the framework has not yet been implemented. The first step will be to derive a set of curves from the market quotes. These are the discounting and forward curves, where the first one describes how future cash flows are discounted and the second curve describes the current view on future interest rates. Both of these will be used for comparison and to price spot and forward starting par swaps as well as off-market swaps. Forward starting swaps are contracts that start in the future, but agreed upon today. Off-market swaps are contracts that are either in the money or out of the money. These two types of contracts can be used to simulate scenarios of termination and novation of swap contracts, and are therefore used to exemplify that it matters how one construct the underlying curves.

While the primary focus of the thesis is to answer the research questions previously mentioned, the actual steps taken to reach these answers are of interest to counterparties of swap agreements since there are plenty of practical pricing issues that need to be dealt with. For instance, if a non-financial corporation were asked to novate its swaps to central clearing it would be valuable to understand the steps and assumptions under the associated costs or lack of costs. In other words, the target audience of this thesis is the general swap market participant.

The main area of contribution of this thesis is an in depth application of a pricing framework for interest rate and cross currency swaps to the Swedish market and furthermore an empirical study highlighting the impact from the use and the type of collateral. Moreover, the study is also conducted for SEK and USD swaps, which is not known to have been done to date.

1.3 Delimitations

As previously mentioned, this thesis will focus on the Swedish swap market with quotes for SEK and USD contracts and no other currencies will therefore be treated. Furthermore, in order to answer the research questions the main issue will be the implementation of an existing framework. There are several ways this implementation can be made. For instance, one could focus solely on the impact on the output depending on the chosen interpolation method. Although a couple of interpolation algorithms were tested, this is not the main focus of this thesis since interpolation is a whole research area in itself. Furthermore, the tenor swap will not be included in the implementation since the aforementioned focus on the interest rate and cross currency swaps does not require additional tenor conditions, in the context of SEK and USD swaps. A final delimitation worth mentioning is the choice to focus the analysis and discussion on the curves for the pricing of different SEK swaps. While the pricing of forward starting and off-market swaps could be done for USD as well, the rationale behind this delimitation is that the pricing of SEK swaps is more relevant for the Swedish market participants. Furthermore, this delimitation also narrows down the width of the results, analysis and discussions in order to make these sections comprehensible to the reader.

1.4 Disposition

The remainder of this thesis is structured as follows: in Section 2 a review of the relevant literature regarding interest rates, discounting, regulatory aspects and swap pricing methods is given. Section 3 then introduces the theoretical framework used in the curve construction. In other words, the section presents the pricing framework of Fujii et al. (2010b) in the context of uncollateralised as well as collateralised swap contracts. Next, Section 4 presents the data that will be used. This section provides an overview of the underlying market instruments and outlines the matters of day count and business days. Section 5 presents the methodology of this thesis. First, the steps of the curve construction method are outlined. Second, the pricing of additional contracts is described. The third part describes the interpolation method applied to the curve construction. Part four provides an overview of the methodological limitations whereas the fifth part reviews the reliability and validity. The sixth and last part of the chapter describes how one can monitor the output curves. Section 6 presents the results of this study alongside some initial analysis. The first part of the section describes the output from the curve construction method. The second part presents the results from the pricing of additional contracts, and the third and last part treats the accuracy of the implementation in terms of replication of the input. In Section 7 the results for each of the research questions are discussed further. Moreover, this section is concluded with a discussion regarding the sustainability of the swap pricing and the use of collateral. Section 8 summarises the findings of this thesis and suggest areas for future research.

2 Literature Review

The first part of the literature review describes the research of the changes in the relationships between interest rates. Next, the research conducted regarding discounting with and without collateral is outlined and is then followed by a review of the regulation that partly explain the increase in collateralised contracts. The literature review is then concluded with a section that outlines the pricing of swaps and puts Fujii et al.'s (2010b) framework in a context.

2.1 Interest Rates and Spreads

One aspect that is covered throughout the literature is the breakdown of interest rate relationships. The financial crisis that erupted in 2007 gave rise to a market environment where previously comparable interest rates diverged. One such relationship that broke down was between rates that shared a common time to maturity, such as interbank offered rates and corresponding OIS rates, as the spreads between these two types increased. This is also true for interest rate swaps with the same maturity but with different floating tenors. Furthermore, rates that were related through implications by other market quotes also deviated. One example is the forward rate agreement (FRA) that could previously be replicated by an implied forward rate derived from deposits. For example, an FRA rate starting in three months and ending in six months could be replicated by two deposits starting today, with one ending in three and the other ending in six months. (Mercurio, 2009)

In an attempt to mend the replication of FRA rates, Bianchetti (2009) introduces the tenor basis spread in the relationship, assuming two curves and no arbitrage. Mercurio (2009) argues that the broken relationship between FRA and implied forward rates does not induce arbitrage opportunities if one takes counterparty credit risk and liquidity issues into account. In other words, the spread could be viewed as the markets expectation regarding these issues. In a similar way Ametrano and Bianchetti (2009) explains the discrepancies as the liquidity and/or default risk inherent in the market. The insight that the interbank market is not risk free and instead prone to the previously mentioned risks results in a built in credit risk premium. Receiving an interest payment with a higher frequency, say six-month Libor semi-annually, should be considered less risky than receiving the corresponding 12-month rate on an annual basis, which is one intuitive way to explain the observed spreads (Gunnarsson, 2013). This postulation is also presented by Morini (2009) and Bianchetti (2009), where the former also proceeds to model the tenor spreads in terms of options of the credit risk associated with a counterparty. Mercurio (2009) also follows a modelling approach and describes the difference between similar rates through the use of a simple credit model, where interbank counterparties are assumed to be able to default.

What are then the implications from the above? Even if the previously broken relationship between interest rates can be remedied through the introduction of credit and liquidity risks, modelling those could prove cumbersome. In the pricing of interest rate swaps, it is instead suggested that one changes the approach from a single curve to a multiple curve framework due to the fact that it is no longer possible to derive forward rates with different tenors from just one curve (Mercurio, 2009; Ametrano and Bianchetti, 2009; Bianchetti, 2009). In other words, one distinct forward curve should be used for each interest rate tenor.

2.2 Discounting and Collateralisation

Although the treatment of forward curves, as outlined in Section 2.1, plays a significant role in the pricing of interest rate derivatives in post-crisis times, the question of how to discount future cash flows is also of great significance. Before the financial crisis, uncollateralised derivatives were mostly discounted using the Libor, which was then believed to be a good proxy for a risk free rate. Now, the collateralisation of OTC contracts has grown significantly, both in bilateral contracts but also through central clearing. This trend is reinforced through regulation such as the Dodd-Frank Act in the United States, under which interest rate swap contracts need to be centrally cleared. (Nashikkar, 2011)

Although the financial crisis can be seen as a catalyst for a change in discounting methods, questions about the validity of using Libor for discounting surfaced earlier. Henrard (2007) questions the then prevailing pre-crisis approach. One example that is brought to attention by the author is the difference in discounting of an interest rate swap and an overnight indexed swap, where the first is discounted using Libor and the second using Libid (London Interbank Bid Rate), which is generally lower than Libor. The author argues that it does not make sense to discount the cash flows differently, especially not if these two contracts are traded with the same counterparty. The usage of multiple discounting curves would then induce arbitrage on an aggregate level. Instead, Henrard (2007) proposes that a market participant should use one discounting curve, where for example an investment bank could use its borrowing rate and a cash rich bank could use the alternative rate it could earn on liquid investments.

Shortly after Henrard's (2007) article was written, the financial crisis hit and as a consequence Henrard (2010) reformulated the problem and proposed a coherent method to value interest rate derivatives. One proposed method is discounting using factors derived from the overnight indexed swaps, which is motivated by the overnight funding and investing of a bank. However, the author also points out that this rate might not reflect the true funding cost in times of market distress. The existence of multiple ways to discount future cash flows is also brought to attention by Ametrano and Bianchetti (2009), who argue that while there is consensus regarding the post-crisis usage of forward curves, it is not the case with discounting. The first method is to discount cash flows as in the old pre-crisis approach, whereas the second is to apply the relevant OIS rates in the case of riskless counterparties or in collateralised agreements. Mercurio (2009) also proposes the use of a risk free rate, of which OIS is a good proxy, in collateralised agreements or where the counterparties are considered to be risk free. The author further argues that the cash flows must be discounted at Libor in the case of an interbank counterparty, in order to reflect the appropriate credit risk.

To summarise the above, much of the literature makes a distinction in terms of funding between uncollateralised and collateralised contracts. However, as mentioned in the introduction of this section, the usage of collateral is growing. Ametrano and Bianchetti (2013) argue that since most interest rate derivatives are collateralised either through bilateral agreements or through central clearing, it is natural to assume that the discounting curve should be constructed using the OIS quotes. The authors furthermore argue that the quotes that one would use to construct discounting and forward curves can be assumed to stem from collateralised contracts, since the market quotations reflect collateralised transactions between financial institutions. This view on OIS discounting for collateralised transactions is reiterated by Hull and White (2013). However, these authors take it one step further and claim that the very same discounting method should be used for non-collateralised transactions as well. The rationale behind this is that the discounting should depend on the risk rather than the funding cost. Furthermore, when computing a risk neutral expected cash flow it is argued to be unreasonable to incorporate the credit risk that is inherent in the Libors.

2.3 Regulation

In this section, the regulatory frameworks of Dodd-Frank and EMIR are described. These are important factors behind the growth of collateralised contracts and are thus relevant for the research questions.

2.3.1 Dodd-Frank

The Dodd-Frank Wall Street Reform and Consumer Protection Act, mostly just known as Dodd-Frank, is a new regulatory framework for OTC derivatives under US law. The Commodity Futures Trading Commission (CFTC) implemented most of the key components that Dodd-Frank highlights during 2013, especially with respect to swap contracts. Both the swap dealers and other major swap market participants are now required to follow a range of requirements such as to determine if they must post collateral to their counterparties. Under the proposed guidance, non-US participants will generally not be subjected to such requirements for swaps entered with non-US counterparties. (Clearly Gottlieb Steen & Hamilton LLP, 2013)

The Commodity Exchange Act (CEA) authorised on the 28th of November 2012 that specific type of swap contracts must be cleared by the Derivative Clearing Organization (DCO). The following interest rate swaps are now mandatory to clear:

- ◇ Plain vanilla interest rate swaps
- ◇ Tenor swaps
- ◇ Forward rate agreements and overnight indexed swaps

The mandatory clearing only applies to interest rate swaps in USD, EUR, GBP and JPY. However, the CFTC plans to make additional clearing determinations in the future. A counterparty in a swap may elect to use the clearing exception if the counterparty is not a financial entity and is using the swap to hedge or mitigate commercial risk. (Clearly Gottlieb Steen & Hamilton LLP, 2013)

By clearing a swap, means that each counterparty will as soon as the swap is executed, submit their sides of the contract to the derivatives clearing organisation, through a clearing broker or directly if they are a member of the DCO. This is done instead of establishing a bilateral contract. The cleared swap is then subject to a marginal requirement decided by the DCO. This includes daily exchanging of cash and upfront posting of securities or cash to cover potential defaults or exposures. (Clearly Gottlieb Steen & Hamilton LLP, 2013)

2.3.2 EMIR

To prevent a new financial crisis, the G20 asked regulators in each country to draft new regulations on OTC derivatives. In a 2009 summit the following statement was issued: "All standardised OTC derivative contracts should be traded on exchanges or electronic trading platforms, where appropriate, and cleared through central counterparties by end-2012 at the latest. OTC derivative contracts should be reported to trade repositories. Non-centrally cleared contracts should be subject to higher capital requirements" (Financial Stability Board, 2012, para. 1). This resulted in what is now known as the European Market Infrastructure Regulation (EMIR) and is covered by the 31 countries of the European economic area, including Lichtenstein and Norway. All derivative counterparties will have to be classified in one of the three categories of which they then follow certain rules. The categories are financial counterparties, non-financial counterparties and non-financial counterparties over the so-called clearing threshold. (European Securities and Markets Authority, 2013)

The regulation under EMIR is extensive, but primarily constructed around three main obligations, similar to the ones of the Dodd-Frank Act:

- Trade reporting of all derivatives transactions
- New risk management measures
- Mandatory clearing of OTC derivatives

The products that are covered by EMIR are all OTC derivatives excluding spot foreign exchange, whereas in the Dodd-Frank Act, foreign exchange forwards are exempted from some obligations. The first obligation of EMIR was implemented by March 2013, whereas the second one was introduced in the autumn of the same year. Clearing is not expected to be mandatory until the end of 2014. (European Securities and Markets Authority, 2013)

2.4 Swap Pricing

This section reviews the literature regarding the pricing of interest rate, tenor and cross currency swaps. This is done in order to put Fujii et al.'s (2010b) framework in a context.

The first research presented focuses on interest rate and cross currency swaps. Boenkost and Schmidt (2005) first show how one can value interest rate swaps without collateral. The authors then describe two separate ways to determine the discount and forward curves underlying the cross currency swaps. In both cases, they argue that the cross currency basis spread must be incorporated in order to price consistently with the market. Moreover, a reference currency must be chosen, in which the forward and discounting curves do not need to be modified but can instead be obtained from the domestic interest rate swap of the currency. The curves from the non-reference currency need to be adjusted, and this is where the authors present the two different methods. The first one keeps the non-reference forward curve intact and adjusts the discount curve to ensure that the cross currency swap can be repriced at par. The second method introduces two discount curves for the non-reference currency, one for the fixed and one for the floating rate cash flows.

Chibane et al. (2009) also introduce a framework for pricing interest rate and cross currency swaps consistently. They motivate the research by the fact that the cross currency spreads, although present before the financial crisis, have increased. Furthermore, the authors argue that the usage of just one discount curve to value a cross currency swap induces arbitrage opportunities. Consequently, they introduce a cross currency swap condition that links discount and forward curves, for both the domestic and foreign sides. The tenor swap is also incorporated for the scenarios where the tenors of the cross currency legs do not equal those of the plain vanilla interest rate swaps. The authors do not, however, cover the pricing of collateralised derivatives but mention that this can be done through OIS discounting.

Articles such as Ametrano and Bianchetti (2009, 2013), Bianchetti (2009) and Mercurio (2009) focus on the single currency pricing. More precisely, the authors present pricing frameworks that treat the non-negligible tenor basis spreads. They emphasise the aforementioned fact that one forward curve has to be derived for each tenor. Therefore it is argued that the tenors of instruments used in the curve construction must be homogenous. This means that in order to construct a three-month forward rate curve, one would have to use instruments with tenors of three months. Ametrano and Bianchetti (2013) also treat the pricing of EUR collateralised EUR swaps and suggest further implementation with collateral currencies different from that of the swap. Through an implementation using EUR quotes, the authors show the difference arising from the tenor spreads. Ametrano and Bianchetti (2013) also state that it is generally the case that the collateralised discount factors differ from the corresponding uncollateralised factors, although this is not shown explicitly.

Fujii et al. (2010b) present a framework that consistently prices interest rate swaps, tenor swaps and cross currency swaps, both with and without collateral agreements. The main contribution compared to Ametrano and Bianchetti (2009), Bianchetti (2009) and Mercurio (2009) in terms of the tenor swaps is the pricing both with and without collateral, as well as the inclusion of the tenor swap condition in the cross currency swap pricing. The cross currency swap part of Fujii et al.'s (2010b) framework can be described as an extension on the cross currency pricing presented by Boenkost and Schmidt (2005) and more importantly Chibane et al. (2009). The main contribution compared to these authors is the inclusion of collateralised agreements. Furthermore, the importance of the choice of collateral currency is emphasised in Fujii et al. (2010a), where the authors argue that it has a non-negligible impact on the pricing. To conclude, Fujii et al.'s (2010b) framework is more generic compared to the previous authors, since it is able to price a multitude of swap variations.

The framework of Fujii et al. (2010b) is implemented by Gunnarsson (2013) in a USD and EUR setting, where the ability to replicate the input swap quotes is evaluated. Furthermore, the author discusses the potential incurred losses for a market participant that does not correctly account for the tenor basis spreads. Gunnarsson (2013) finds that not accounting for the tenor basis spreads could lead to losses up to several per cent of the notional amount.

3 Theoretical Framework

In light of the presentation of the swap pricing literature in Section 2.4, the curve construction framework used in this thesis will now be presented. The derivations made by Fujii et al. (2010b) of the underlying discounting factors and forward rates are first presented in the case where no collateral agreements are present, and are then followed by the derivations corresponding to the collateralised contracts.

3.1 Uncollateralised Swap Pricing Framework

The uncollateralised contracts that will now be presented consist of the plain vanilla interest rate swap, the tenor swap and the cross currency swap. The previously negligible basis spreads are incorporated in the last two swap contracts.

3.1.1 Plain Vanilla Interest Rate Swap

The plain vanilla interest rate swap is a contract between two parties to exchange fixed and floating interest rate payments based on a common notional amount. In this case, one party is the fixed rate payer and floating rate receiver, whereas the other is the fixed rate receiver and floating rate payer. These two legs are often denoted payer and receiver, referring to the fixed rate. The floating rate of the contract is linked to an interest rate benchmark such as the three-month Stibor fixing for SEK or the three-month Libor fixing for USD, while the fixed rate is determined at the initiation of the contract in order to ensure that the present value for the two counterparties entering the interest rate swap is equal to zero. It is worth noting that the notional amounts do not change hands. Under the assumption made by Fujii et al. (2010b) that the payment dates of both swap legs coincide, the resulting condition for the interest rate swap is given by Eq. (3.1).

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t[L(T_{n-1}, T_n)] P_{t,T_n} \tag{3.1}$$

Here, C_{t,T_N} is the fixed rate for an interest rate swap at time t with maturity T_N. Δ_{T_{n-1},T_n} and δ_{T_{n-1},T_n} are the day count factors between times T_{n-1} and T_n for the fixed and floating legs, respectively. P_{t,T_n} is the discount factor from time T_n to time t. $L(T_{n-1}, T_n)$ is the interbank offered rate fixing underlying the floating rate between T_{n-1} and T_n. For instance, in the case of a SEK swap, $L(T_{n-1}, T)$ is the three-month Stibor rate between the two dates. $E_t[.]$ is the expectation given information at time t with $P_{t,T}$ as numeraire. As previously mentioned, in the pre-crisis setting the interbank offered rate was considered a good proxy for the risk free rate and was therefore used as the discounting rate. Then, the following condition for an interbank offered rate and the corresponding discount factor holds:

$$L(T_{n-1}, T_n) = \frac{1}{\delta_{T_{n-1},T_n}} \left(\frac{1}{P_{T_{n-1},T_n}} - 1 \right) \tag{3.2}$$

By using the no-arbitrage condition between discount factors, Eq. (3.2) can be rewritten as the following:

$$L(T_{n-1}, T_n) = \frac{1}{\delta_{T_{n-1},T_n}} \left(\frac{P_{t,T_{n-1}}}{P_{t,T_n}} - 1 \right) \tag{3.3}$$

In order to illustrate the no-arbitrage condition, one can consider the following strategy:

- ◇ At time t, enter a long position in a zero coupon bond with maturity at time T_n and face value 1. The price paid for this position is P_{t,T_n}
- ◇ At time t, also enter a short position in a zero coupon bond with maturity at time T_{n-1} and face value $P_{t,T_n}/P_{t,T_{n-1}}$. The initial cash flow received for this position is P_{t,T_n} and thus matches the price paid for the previously mentioned long position.
- ◇ Discounting the payoff of one from time T_n to time T_{n-1} yields that P_{T_{n-1},T_n} equals $P_{t,T_n}/P_{t,T_{n-1}}$.

By inserting Eq. (3.3) in Eq. (3.1) one can clearly see the telescopic property of the sum, which results in

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n} = P_{t,T_0} - P_{t,T_N} \tag{3.4}$$

where P_{t,T_0} is the discount factor from the start date to the effective date, which can be computed by using the appropriate overnight rate. Next, Eq. (3.4) can be rearranged to the following:

$$P_{t,T_N} = \frac{P_{t,T_0} - C_{t,T_N} \sum_{n=1}^{N-1} \Delta_{T_{n-1},T_n} P_{t,T_n}}{1 + C_{t,T_N} \Delta_{T_{N-1},T_N}} \tag{3.5}$$

It is now possible to determine the discounting factors inherent in the swap quotes by iteratively working through Eq. (3.5), for maturities $T_1, ..., T_N$. Then the forward rates can be determined through Eq. (3.3). By interpolating these two sets of outputs, continuous discount and forward curves can be obtained. However, a practical issue that one could face when applying the curve construction procedure to market quotes is the fact that not all necessary maturities are traded. There are a number of ways to integrate interpolation methods in the curve construction procedure to deal with this issue, as will be seen later on.

3.1.2 Tenor Swap

The tenor swap is a contract where two parties exchange interest rate amounts based on floating reference rates with different tenors. For instance, in the case of a SEK tenor swap, one party could pay the three-month Stibor and receive the one-month Stibor plus an additional tenor basis spread. The general convention is to add the tenor basis spread to the leg with the shorter tenor (Fujii et al., 2011). Its size is determined in order to ensure that the present value of the contract is equal to zero at initiation. Just as in the case of the fixed for floating interest rate swap, the underlying notional amount does not change hands. In a market with interest rate swaps and tenor swaps, the consistency conditions given in Fujii et al. (2010b) are the following:

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t[L^{3m}(T_{n-1}, T_n)] P_{t,T_n} \tag{3.6}$$

$$\sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t[L^{3m}(T_{n-1}, T_n)] P_{t,T_n} = \sum_{k=1}^{K} \delta_{T_{k-1},T_k} (E_t[L^{1m}(T_{k-1}, T_k)] + \tau_K) P_{t,T_k} \tag{3.7}$$

In Eq. (3.6) and Eq. (3.7), the superscripts $1m$ and $3m$ are added to emphasise the tenors of the underlying floating interest rates. τ_K is the tenor basis spread previously mentioned. Furthermore, it could be assumed that the three-month Stibor is paid on a quarterly basis, whereas the one-month Stibor is paid on a monthly basis, thus $K = 3N$. By combining Eq. (3.6) and Eq. (3.7), and again eliminating the floating parts through the previously described no-arbitrage assumption, one can sequentially determine the discounting factors through Eq. (3.8). The sets of three-month and one-month forward rates can then be determined as before. The discount and forward curves can then be constructed by interpolating these sets.

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n} = P_{t,T_0} - P_{t,T_K} + \tau_K \sum_{k=1}^{K} \delta_{T_{k-1},T_k} P_{t,T_k} \tag{3.8}$$

As mentioned in the delimitation section of this thesis, the tenor swap will not be included in the implementation. As will be seen, the USDSEK cross currency swap is based on floating tenors of three months both for the SEK and the USD leg. In other words, the tenor swap is made redundant in this setting since these tenors match those of the SEK and USD IRS. However, it is included in this section due to the fact that the instrument is part of the framework. But, if for instance one were to look at the EURUSD cross currency swap, the tenor swap condition would have to be taken into account since there is a floating tenor mismatch between the EUR IRS (six months) and the EURUSD CCS (both sides have tenors of three months).

3.1.3 Cross Currency Swap

The cross currency swap is a contract between two parties to exchange interest rate payments in two different currencies. For instance, one party could pay in USD the three-month Libor to receive in SEK the three-month Stibor plus an additional cross currency basis spread. In contrast to the previous two swap contracts, the notional amounts switch hands at the initiation of the swap and then switch back at the maturity of the contract. The cross currency basis spread is determined and applied to one of the legs in order for the present value of the contract at initiation to equal zero. In a setting with a SEK plain vanilla interest rate swap and a USDSEK cross currency swap, the consistency conditions as defined by Fujii et al. (2010b) are as follows:

$$C_{t,T_N}\sum_{n=1}^{N}\Delta_{T_{n-1},T_n}P_{t,T_n}=\sum_{n=1}^{N}\delta_{T_{n-1},T_n}E_t[L(T_{n-1},T_n)]P_{t,T_n} \tag{3.9}$$

$$N_{SEK}\left(-P_{t,T_0}+\sum_{n=1}^{N}\delta_{T_{n-1},T_n}\left(E_t[L(T_{n-1},T_n)]+b_N\right)P_{t,T_n}+P_{t,T_N}\right)=$$
$$f_x(t)\left(-P^{\$}_{t,T_0}+\sum_{n=1}^{N}\delta^{\$}_{T_{n-1},T_n}E^{\$}_t[L^{\$}(T_{n-1},T_n)]P^{\$}_{t,T_n}+P^{\$}_{t,T_N}\right) \tag{3.10}$$

In the above conditions, N_{SEK} is the SEK notional per USD at initiation, $f_x(t)$ is the USDSEK exchange rate at time t and b_N is the cross currency basis spread. The superscript \$ in Eq. (3.10) represent the USD leg of the cross currency swap. Furthermore, it is assumed that the floating tenors of the domestic and foreign interest rate swaps are the same. If this is not the case, a remedy would be to add the relevant tenor swap condition. Under the assumption that Libor is the discounting rate, one can see that the right-hand side of Eq. (3.10) is equal to zero. By rearranging the same equation and eliminating the floating part through the use of Eq. (3.9) one get the following:

$$P_{t,T_N}=\frac{P_{t,T_0}-\sum_{n=1}^{N-1}(C_{t,T_N}\Delta_{T_{n-1},T_n}+b_N\delta_{T_{n-1},T_n})P_{t,T_n}}{1+C_{t,T_N}\Delta_{T_{N-1},T_N}+b_N\delta_{N-1,N}} \tag{3.11}$$

Again, one can determine P_{t,T_N} in an iterative manner to obtain the set of discounting factors and thus the forward rates. However, if Stibor is used as a discounting rate instead of Libor, the procedure is a bit different. Apart from the conditions of Eq. (3.9) and Eq. (3.10), one will also need an additional condition for the domestic USD interest rate swap:

$$C^{\$}_{t,T_N}\sum_{n=1}^{N}\Delta^{\$}_{T_{n-1},T_n}P^{\$}_{t,T_n}=\sum_{n=1}^{N}\delta^{\$}_{T_{n-1},T_n}E^{\$}_t[L^{\$}(T_{n-1},T_n)]P^{\$}_{t,T_n} \tag{3.12}$$

One can immediately see that the SEK discounting and forward curve can be determined directly through Eq. (3.9), since the same arguments made in the case of a domestic plain vanilla interest rate swap outlined in section Section 3.1.1 now holds. But in order to determine the USD discounting and forward curve in this setting, one needs to use the condition in Eq. (3.10). The right-hand side is no longer equal to zero. Instead the left-hand side reduces to $N_{SEK}b_N\sum_{n=1}^{N}\delta_{T_{n-1},T_n}P_{t,T_n}$. By using this fact together with the condition of Eq. (3.12), the USD discounting factors can be sequentially determined through the following:

$$P^{\$}_{t,T_N}=\frac{P^{\$}_{t,T_0}-C^{\$}_{t,T_N}\sum_{n=1}^{N-1}\Delta^{\$}_{T_{n-1},T_n}P^{\$}_{t,T_n}+\frac{N_{SEK}}{f_x(t)}\sum_{n=1}^{N}b_N\delta_{T_{n-1},T_n}P_{t,T_n}}{1+C^{\$}_{t,T_N}\Delta^{\$}_{T_{N-1},T_N}} \tag{3.13}$$

The forward rates can then be determined as before. As noted by Fujii et al. (2010b), the above result is interesting in the sense that it shows dependence among domestic markets. Eq. (3.13) explicitly shows the interdependence between USD and SEK discounting factors. Please note that in the remainder of this thesis, it is assumed that the cross currency swap contracts consist of constant notional amounts. An introduction to the case of mark-to-market cross currency swaps can be found in Fujii et al. (2010b).

3.2 Collateralised Swap Pricing Framework

In this section the swap pricing framework is outlined in the presence of collateral agreements. In order to do so, it is necessary to first outline the theory regarding the pricing of collateralised products. The theory is based on the overview provided by Fujii et al. (2010b) while an overview of stochastic differential equations can be found in literature such as Björk (2009). The mechanics of a collateral agreement between two counterparties, A and B, is that if the value of the contract turns positive for A, then B must post collateral matching that value. Party A then pays a collateral rate to B that is based on the posted collateral. This is usually the relevant overnight rate. Party A can then invest the received collateral, for instance in the risk free rate in order to earn the difference between the two rates. Due to this setup, the posted collateral can essentially be described as a loan. In order to determine the process of the collateral account as in Fujii et al. (2010b), let $V(t)$ be value of the collateral account at time t, $c(t)$ the collateral rate, $r(t)$ the risk free rate, $h(t)$ the value of a derivative at time t and $a(t)$ the number of positions in the aforementioned derivative, then the dynamics of a collateral account with continuous posting and perfect collateralisation can be described by the stochastic differential equation

$$dV(s) = (r(s) - c(s))V(s)ds + a(s)dh(s) \tag{3.14}$$

where it is also assumed that the collateralisation is made continuously and without any clearing threshold. Eq. (3.14) can be interpreted as follows: The change in value of the collateral account depends on the interest differential earned on the posted collateral over time as well as the change in the value of the $a(s)$ underlying derivatives. As shown in the complete version of the derivations in Appendix A, the present value of a derivative h, given the information at time t and with the expectation taken using the money market account as numeraire is as follows:

$$h(t) = E_t\left[e^{-\int_t^T c(s)ds} h(T)\right] \tag{3.15}$$

If one instead considers a collateral account where the collateral is posted in a foreign currency, the corresponding stochastic differential equation describing the collateral account is:

$$dV^f(s) = (r^f(s) - c^f(s))V^f(s)ds + a(s)d\left(\frac{h(s)}{f_x(s)}\right) \tag{3.16}$$

where the superscript f indicates the foreign currency and $f_x(s)$ is the exchange rate at time s. Again, by applying the procedure outlined in Appendix A one can see that the present value of the derivative given the information at time t and expressed in the domestic currency is:

$$h(t) = E_t\left[e^{-\int_t^T r(s)ds} e^{\int_t^T (r^f(s) - c^f(s))ds} h(T)\right] \tag{3.17}$$

As noted by Fujii et al. (2010b), the overview outlined above provides further justification for the discontinuation of Libor as a discounting rate. In the presence of collateral one must instead discount using the collateral rate, which is determined by the overnight rate. This derivation of the discount factors under this new discounting method is outlined in Section 3.2.1 and is then applied to the remainder of this chapter.

3.2.1 Overnight Indexed Swap

Due to the fact that a collateralised agreement can be considered risk free, the interest rate paid on the collateral is often tied to the relevant overnight rate for the currency of the contract (Piterbarg, 2010). One could then argue that since the collateral earns the overnight rate, which is the best proxy for a risk free rate, the discount factors should be determined from the corresponding overnight indexed swaps (Nashikkar, 2011). These swaps exchange a fixed for a floating interest rate, where the latter is based on a compounded overnight rate. If one assumes a continuously compounded overnight rate, the condition of the overnight indexed swap as described in Fujii et al. (2010b) is the following:

$$S_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} E_t \left[e^{-\int_t^{T_n} c(s)ds} \right] = \sum_{n=1}^{N} E_t \left[e^{-\int_t^{T_n} c(s)ds} \left(e^{\int_{T_{n-1}}^{T_n} c(s)ds} - 1 \right) \right] \quad (3.18)$$

Here, Δ_{T_{n-1},T_n} is the day count factor between times T_{n-1} and T_n as before. $c(s)$ is the overnight rate, and thus also the rate received (paid) on posted (received) collateral. S_{t,T_N} is the fixed rate determined in order for the two legs to be equal at the initiation of the swap contract. If one defines the OIS discount factor between times t and T_n as

$$D_{t,T_n} = E_t \left[e^{-\int_t^{T_n} c(s)ds} \right] \quad (3.19)$$

then Eq. (3.18) can be written as

$$S_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = \sum_{n=1}^{N} (D_{t,T_{n-1}} - D_{t,T_n}) \quad (3.20)$$

The new notation for the discounting factor is applied in order to emphasise the distinction from the uncollateralised case. Due to the telescopic property of the sum in the right-hand side of Eq. (3.20), the equation reduces to

$$S_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = D_{t,T_0} - D_{t,T_N} \quad (3.21)$$

The discount factors can then be determined by sequentially solving the following:

$$D_{t,T_N} = \frac{D_{t,T_0} - S_{t,T_N} \sum_{n=1}^{N-1} \Delta_{T_{n-1},T_n} D_{t,T_n}}{1 + S_{t,T_N} \Delta_{T_{N-1},T_N}} \quad (3.22)$$

These discount factors will then be used throughout the remainder of this section, and the discounting curve and the forward curve(s) are now separated.

3.2.2 Collateralised Plain Vanilla Interest Rate Swap

The collateralised plain vanilla interest rate swap conditions given in Fujii et al. (2010b) are the following:

$$S_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = D_{t,T_0} - D_{t,T_N} \tag{3.23}$$

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t^c[L(T_{n-1}, T_n)] D_{t,T_n} \tag{3.24}$$

In this case, Eq. (3.23) is the OIS condition used to derive the discount factors whereas Eq. (3.24) is the interest rate swap condition. $E_t^c[.]$ is the expectation given the information available at time t in the collateralised setting, where $D_{t,T}$ is the numeraire. By first determining the OIS discounting factors from Eq. (3.23), the forward rates can be determined through Eq. (3.24). Here it assumed that the OIS swaps are quoted with maturities matching those of the plain vanilla interest rate swap. Note that the telescopic property previously used for the uncollateralised plain vanilla interest rate swap does not hold in Eq. (3.24) due to the fact that the forward rates and discount factors now stem from two different curves. To clarify the above procedure, the forward curve is not derived from the discounting curve. As described by Fujii et al. (2010b), the collateral currency is often chosen to be the same as the one in which the swap is quoted.

3.2.3 Collateralised Tenor Swap

The collateralised analogue of the tenor swap conditions in Eq. (3.6) and Eq. (3.7) are the following:

$$S_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = D_{t,T_0} - D_{t,T_N} \tag{3.25}$$

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t^c[L^{3m}(T_{n-1}, T_n)] D_{t,T_n} \tag{3.26}$$

$$\sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t^c[L^{3m}(T_{n-1}, T_n)] D_{t,T_n} = \sum_{k=1}^{K} \delta_{T_{k-1},T_k} (E_t^c[L^{1m}(T_{k-1}, T_k)] + \tau_K) D_{t,T_k} \tag{3.27}$$

By first determining the discount factors from Eq. (3.25) and then combining Eq. (3.27) and Eq. (3.26), one can determine the desired forward rates. Again, the assumption regarding the choice of collateral currency outlined in the case of a collateralised plain vanilla interest rate swap applies. As previously mentioned in Section 3.1.2, the tenor swap will not be treated further, but is again included in this overview since it is an essential part of the pricing framework.

3.2.4 Collateralised Cross Currency Swap

The collateralised cross currency swap introduces the setting in which collateral could be posted in different currencies depending on the agreement. In this setting Fujii et al. (2010b) assume that the effective federal funds rate is the risk free interest rate in order to simplify the procedure slightly. This is the same interest rate used for USD collateral and implies that

$$D^{\$}_{t,T_n} = E_t\left[e^{-\int_t^{T_n} c^{\$}(s)ds}\right] = E_t\left[e^{-\int_t^{T_n} r^{\$}(s)ds}\right] = P^{\$}_{t,T_n} \tag{3.28}$$

Furthermore, the pricing expression of Eq. (3.17) will then reduce to

$$h(t) = E_t\left[e^{-\int_t^T r(s)ds} e^{\int_t^T (r^{\$}(s)-c^{\$}(s))ds} h(T)\right] = E_t\left[e^{-\int_t^T r(s)ds} h(T)\right] \tag{3.29}$$

To recap Section 3.2.2, the conditions for a domestic SEK IRS collateralised in SEK are

$$S_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = D_{t,T_0} - D_{t,T_N} \tag{3.30}$$

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t^c[L(T_{n-1},T_n)] D_{t,T_n} \tag{3.31}$$

whereas the corresponding conditions for a domestic USD IRS collateralised in USD are

$$S^{\$}_{t,T_N} \sum_{n=1}^{N} \Delta^{\$}_{T_{n-1},T_n} P^{\$}_{t,T_n} = P^{\$}_{t,T_0} - P^{\$}_{t,T_N} \tag{3.32}$$

$$C^{\$}_{t,T_N} \sum_{n=1}^{N} \Delta^{\$}_{T_{n-1},T_n} P^{\$}_{t,T_n} = \sum_{n=1}^{N} \delta^{\$}_{T_{n-1},T_n} E_t^c[L^{\$}(T_{n-1},T_n)] P^{\$}_{t,T_n} \tag{3.33}$$

In both these cases one can of course derive the relevant sets of discount factors as outlined in Section 3.2.2. However, if one wishes to derive the SEK interest rates under USD collateral, the USDSEK cross currency condition in Eq. (3.34) is added with the use of Eq. (3.29).

$$\begin{aligned} N_{SEK}\left(-P_{t,T_0} + \sum_{n=1}^{N} \delta_{n-1,n}\left(E_t[L(T_{n-1},T_n)] + b_N\right) P_{t,T_n} + P_{t,T_N}\right) = \\ f_x(t)\left(-P^{\$}_{t,T_0} + \sum_{n=1}^{N} \delta^{\$}_{n-1,n} E^{\$}_t[L(T_{n-1},T_n)] P^{\$}_{t,T_n} + P^{\$}_{t,T_N}\right) \end{aligned} \tag{3.34}$$

Although the right-hand side of Eq. (3.34) is already known, additional conditions are required to be able to determine both the discount factors and forward rates of the left-hand side. As pointed out by Fujii et al. (2010b), these unknowns can be determined if there exist market quotes of domestic SEK IRS with USD as the collateral currency. The corresponding condition is the following:

$$\widehat{C}_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t^c[L(T_{n-1},T_n)] P_{t,T_n} \tag{3.35}$$

In Eq. (3.35) $\widehat{C}_{t,T_N}$ is the swap rate of a USD collateralised SEK IRS. By combining Eq. (3.34) and Eq. (3.35) one get that

$$N_{SEK}\left(-P_{t,T_0}+\widehat{C}_{t,T_N}\sum_{n=1}^{N}\Delta_{T_{n-1},T_n}P_{t,T_n}+\sum_{n=1}^{N}\delta_{n-1,n}b_N P_{t,T_n}+P_{t,T_N}\right)=$$
$$f_x(t)\left(-P^{\$}_{t,T_0}+\sum_{n=1}^{N}\delta^{\$}_{n-1,n}E^{\$}_t[L(T_{n-1},T_n)]P^{\$}_{t,T_n}+P^{\$}_{t,T_N}\right) \tag{3.36}$$

meaning that all is known except for the set of discount factors $\{P_{t,T}\}$ which can now be sequentially determined in a way similar to the one in Section 3.1.3. One can then determine the forward rates of the left-hand side of Eq. (3.34). Through interpolation, one can then obtain the continuous set of discount factors and forward rates.

Unfortunately, it is not always the case that there exist quotes of domestic swaps with foreign collateral currencies. One way to deal with this problem is to approximate the expected forward rates under the foreign collateral with the derived forward rates when using the domestic currency as collateral. In other words, one could make the following approximation:

$$E_t[L(T_{n-1},T_n)]\approx E^c_t[L(T_{n-1},T_n)] \tag{3.37}$$

As described by Fujii et al. (2010b) this approximation neglects the change in numeraire and is warranted if the SEK risk free rate and the overnight interest rates display similar dynamic properties. Another option mentioned by the authors is to use foreign exchange forwards to transform the foreign discount factors into the domestic discounting factors of the left-hand side in Eq. (3.34), given that these instruments are sufficiently liquid.

4 Data

This section will introduce the data used in this thesis. Before the methods used to answer the research questions are presented, it is essential to present the market quotes and describe the underlying instruments. The entire set of data used in the thesis is secondary. It is a snapshot of the market as of 3 December 2013 (with spot date 5 December 2013) and is provided by a Swedish institution, which is not disclosed for business reasons. The available market quotes that will be described in the remainder of this section are of the following instruments:

- Deposits
- Forward rate agreements
- Plain vanilla interest rate swaps
- Cross currency swaps
- Overnight indexed swaps
- Foreign exchange forwards

One could ask if a sample of market quotes from just one day is enough to apply a framework and be able to draw valid conclusions. The description of the implementation phase is not highly dependable on the quality of the data, as the steps that will be outlined later still apply. The question regarding the ability to draw valid conclusion, on the other hand, is warranted. However, the market for interest rate and cross currency swaps is characterised by large volumes. A survey of the fixed income markets from the Swedish central bank show that the average daily turnover in the Swedish market of SEK plain vanilla interest rate swaps is 46.8 billion whereas the corresponding turnover for SEK cross currency swaps is 1.2 billion (Sveriges Riksbank, 2013). Furthermore, the data indicates that USD is one of the most important currencies besides SEK. It is thus concluded that the swap quotes are liquid enough to be absent of large anomalies, and one can therefore draw valid conclusions.

In the curve construction procedure, all of the aforementioned instruments will be used at some point in the construction of the discounting and forward curves. Ametrano and Bianchetti (2013) provide an extensive overview of these instruments, and thus constitute much of the basis of the overview that will follow in this chapter. In addition to the available instruments mentioned above, Ametrano and Bianchetti (2013) also describe synthetic instruments, which are derived from the other market quotes. These will also be described later on.

As described by Ametrano and Bianchetti (2013), different market instruments can inherent quite different characteristics, for instance regarding tenors as well as liquidity and credit risk. Thus, the authors propose that one chooses the market instruments with the least degree of overlap and the highest degree of liquidity as inputs when building the curves. The instruments used in the curve construction procedure will be described later on in this section. But in order to understand the basis of the market instruments, it is essential to first describe the underlying interest rate benchmarks. These are outlined in the next section.

4.1 Interest Rate Benchmarks

There are two interest rate benchmarks that are underlying for the market quotes used in this thesis. The first one is the London Interbank Offered Rate, denoted Libor. It is defined as "the rate at which an individual contributor panel bank could borrow funds, were it to do so by asking for and then accepting interbank offers in reasonable market size, just prior to 11.00am London time" (British Bankers' Association, 2014, para. 2). The interest rate fixings are determined by a number of banks' London branches and covers a number of currencies and maturities, which both have been reduced in the aftermath of the recent Libor manipulation scandal. In the remainder of the thesis, the term Libor is used as a reference to the USD Libor unless stated otherwise.

The second interbank interest rate fixing used in the thesis is the Stockholm Interbank Offered Rate, or Stibor for short. It is overseen by the Swedish Bankers' Association and is an average of the rate at which the participating banks' are willing lend unsecured SEK to other participating banks (Swedish Bankers' Association, 2013). Although there are a lot of similarities with Libor, one interesting difference is that while Stibor banks estimate the cost of lending, the Libor banks determine their perceived funding costs.

The Libor and Stibor rates are used as the underlying rates for a vast number of financial products. In this thesis, they appear as the determinants of the floating legs in the plain vanilla interest rate and cross currency swaps. Furthermore, the deposits and forward rate agreements are also based on these. However in the case of the overnight indexed swaps the floating legs are determined by compounded overnight interest rates. For the USD overnight indexed swaps, the underlying rate is the effective federal funds rate, which is calculated by the Federal Reserve Bank of New York as an average rate on trades arranged by large brokers. The overnight rate corresponding to the SEK overnight indexed swap is the Stibor T/N (Tomorrow Next) Average rate, often denoted as Stina. (Henrard, 2013)

4.2 Deposits

A deposit is an uncollateralised zero coupon over the counter contract, where one party pays the notional amount at a certain spot date to receive the notional plus an annually compounded interest rate at maturity. The deposit instrument is suitable for the construction of the short end of a discount curve and the corresponding discounting factor can be determined through Eq. (4.1). (Ametrano and Bianchetti, 2013)

$$P_{t,T_n} = \frac{P_{t,T_0}}{1 + \delta^D_{T_0,T_n} R^D_{T_0,T_n}} \tag{4.1}$$

Here t, T_0 and T_n are todays date, the spot date and maturity date, respectively. $R^D_{T_0,T_n}$ is the deposit rate between the spot and maturity dates and $\delta^D_{T_0,T_n}$ is the day count factor of the same period. The deposit data used in the curve construction procedure is from the SEK and USD market with interest rate tenors of three months, meaning that the rates used are based on the three-month fixings of Stibor and Libor.

Note that since the deposit contracts are uncollateralised, they will not be used to construct the discounting curve of collateralised products. The available deposit quotes are shown in Table 4.1.

Maturity	Quote (SEK)	Quote (USD)
3M	1.08%	0.24%

Table 4.1: Deposit Quotes as per 3 December 2013.

4.3 Forward Rate Agreements

A forward rate agreement could be described as a deposit agreed upon today and effective in the future. These are also traded over the counter. The FRA contracts are often used in a curve construction procedure to generate discount factors corresponding to the short end of the curve. This is done through the relationship visualised in Eq. (4.2). (Ametrano and Bianchetti, 2013)

$$P_{t,T_n} = \frac{1}{1 + \delta^F_{T_{n-1},T_n} R^F_{T_{n-1},T_n}} \cdot P_{t,T_{n-1}} \tag{4.2}$$

In Eq. (4.2) t is today's date whereas T_0, T_{n-1} and T_n are the spot, forward start and maturity dates of the contract, respectively. $R^F_{T_{n-1},T_n}$ is the forward rate of the contract between times T_{n-1} and T_n and $\delta^F_{T_{n-1},T_n}$ is the day count factor associated with the same interval. As apparent from Eq. (4.2) the discounting could be said to be done in two steps, first to the forward start date T_{n-1} and then to todays date. The FRA quotes available in the curve construction procedure are from the SEK and USD market, spanning three-month periods with maturities from six to 24 months. In other words, the contracts are not overlapping with the previously described deposits. The available FRA quotes are shown in Table 4.2.

Period	Quote (SEK)	Quote (USD)
3M 6M	1.10%	0.25%
6M 9M	1.25%	0.51%
9M 12M	1.34%	0.70%
12M 15M	1.45%	0.79%
15M 18M	1.58%	0.92%
18M 21M	1.71%	1.09%
21M 24M	1.85%	1.30%

Table 4.2: Forward Rate Agreement Quotes as per 3 December 2013.

4.4 Plain Vanilla Interest Rate Swaps

The plain vanilla interest rate swaps are described in Section 3.1 and Section 3.2, and these are quoted in terms of the fixed rates. The quoted maturities in the available data span from two to 30 years and consequently the swaps are used to determine the long end of the discount and forward curves. The available SEK and USD interest rate swap quotes are shown in Table 4.3.

Maturity	Quote (SEK)	Quote (USD)
2Y	1.33%	0.38%
3Y	1.57%	0.67%
4Y	1.81%	1.07%
5Y	2.02%	1.50%
6Y	2.20%	1.89%
7Y	2.35%	2.21%
8Y	2.48%	2.48%
9Y	2.58%	2.69%
10Y	2.66%	2.87%
12Y	2.79%	3.14%
15Y	2.91%	3.40%
20Y	2.99%	3.62%
25Y	3.00%	3.72%
30Y	3.01%	3.78%

Table 4.3: Interest Rate Swap Quotes as per 3 December 2013.

4.5 Cross Currency Basis Spreads

The cross currency swaps are outlined in Section 3.1 and Section 3.2, and these are quoted in terms of the cross currency basis spread, which is added to one of the legs to price the contract at par. The tenors of the two legs of the USDSEK cross currency swap are three months. The available cross currency basis spread quotes are shown in Table 4.4.

Maturity	Quote
15M	-0.10%
18M	-0.10%
2Y	-0.09%
3Y	-0.07%
4Y	-0.05%
5Y	-0.02%
6Y	-0.01%
7Y	0.00%
10Y	0.03%
12Y	0.06%
15Y	0.11%
20Y	0.17%
25Y	0.20%
30Y	0.23%

Table 4.4: Cross Currency Basis Spread Quotes as per 3 December 2013.

4.6 Overnight Indexed Swaps

The overnight indexed swap quotes can be used to construct discounting curves in the collateralised case, as was described in Section 3.2.1. As can be seen in Table 4.5, both the SEK and USD overnight indexed swaps quotes are available for maturities of overnight (ON), tomorrow next (TN), second next (SN) and then for yearly maturities from one to ten years. This is in sharp contrast to the final maturity of 30 years for the interest rate swaps and cross currency swaps. The reason why there are no maturities above ten years for the overnight indexed swaps is that there is practically no market beyond this level. This poses a problem if one wishes to compare the uncollateralised and collateralised pricing frameworks for maturities above ten years, since the yearly market pillars from year 11 to 30 need to be estimated somehow. This estimation will be described in Section 4.8 where the so-called synthetic instruments are introduced.

Maturity	Quote (SEK)	Quote (USD)
ON/TN/SN	1.04%	0.09%
1Y	0.95%	0.10%
2Y	1.12%	0.18%
3Y	1.34%	0.44%
4Y	1.57%	0.82%
5Y	1.77%	1.22%
6Y	1.95%	1.6%
7Y	2.11%	1.91%
8Y	2.23%	2.17%
9Y	2.34%	2.38%
10Y	2.42%	2.55%

Table 4.5: Overnight Indexed Swap Quotes as per 3 December 2013.

4.7 Foreign Exchange Forwards

A foreign exchange forward is a contract to exchange one currency for another at a future time. It can be expressed as a ratio of a domestic and a foreign discount factor as defined in Eq. (4.3) (Fujii et al., 2010c, 2011).

$$f_x^{(i,j)}(t, T_N) = f_x^{(i,j)}(t) \frac{P_{t,T_N}^{(j)}}{P_{t,T_N}^{(i)}} \tag{4.3}$$

Here, $f_x^{(i,j)}(t, T_N)$ is the forward exchange rate between currency i and j, and $f_x^{(i,j)}(t)$ is the spot rate of exchange. $P_{t,T_N}^{(\cdot)}$ is the uncollateralised domestic discount factor for the given currency. The available quotes are shown in Table 4.6 and are given on the form

$$\frac{f_x^{(i,j)}(t, T_N)}{f_x^{(i,j)}(t)} = \frac{P_{t,T_N}^{(j)}}{P_{t,T_N}^{(i)}} \tag{4.4}$$

where currency i corresponds to USD and currency j corresponds to SEK.

Maturity	Quote
1M	100.07%
2M	100.13%
3M	100.18%
4M	100.24%
5M	100.30%
6M	100.36%

Table 4.6: Foreign Exchange Forward Quotes as per 3 December 2013.

4.8 Synthetic Instruments

Ametrano and Bianchetti (2013) use the term synthetic instruments for contracts that are not quoted themselves, but are rather derived from other market quotes. These are essentially constructed in order to facilitate the curve construction process. The authors further divide the instruments into three categories; synthetic deposits, synthetic FRAs and synthetic interpolated or extrapolated instruments.

The synthetic interpolated or extrapolated instruments are going to be used in this thesis, and these are constructed by interpolating or extrapolating from a set of given market quotes. As pointed out by Ametrano and Bianchetti (2013), interpolations are often performed in swap quotes in order to fill in the missing maturities. They also argue that brokers often use this method. The procedure is quite intuitive and very simple to perform. Furthermore, interpolation in swap quotes can greatly reduce the complexity of the curve construction procedure, due to the fact that the interpolation is moved from within the procedure to the very top.

While the interpolation method of constructing synthetic swap quotes is used in the case of missing intermediate market pillars, an extrapolating method is applied in order to estimate the missing overnight indexed swap quotes with yearly maturities greater than ten years. This is done due to the previously mentioned fact that there is practically no OIS market beyond a maturity of ten years. In order to be able to perform the implementation of Fujii et al.'s (2010b) framework and the subsequent comparisons for maturities past ten years the OIS quotes are extrapolated up to 30 years, thus matching the final maturity of the IRS quotes. The extrapolation is done by assuming a constant spread between IRS and OIS quotes after ten years, and is described further in the collateralised curve construction method of Section 5.1.3.

4.9 Day Count and Business Days

In order to use the market data to derive the curves, there are a couple of assumptions that have to be made. First of all, one has to decide how to count the number of interest bearing days in a given period. To obtain the day count factors that were mentioned in the presentation of the framework, the interest bearing days are divided by the total number of days in a year.

There are several ways to calculate the day count factors, but the two methods that are used in this thesis are the ACT/360 and 30/360 methods, as defined in Henrard (2013). The day count factor between two dates according to the ACT/360 method is

$$\frac{d_2 - d_1}{360} \tag{4.5}$$

where $d_2 \geq d_1$ are the start and end dates under consideration. The day count factor according to the 30/360 method is defined as

$$\frac{360(Y_2 - Y_1) + 30(M_2 - M_1) + (D_2 - D_1)}{360} \tag{4.6}$$

where $Y_2 \geq Y_1$, $M_2 \geq M_1$ and $D_2 \geq D_1$ denote the years, months and days of the end and start dates respectively. Furthermore, for the 30/360 method there are different rules to apply to the cases when for instance the start or end dates are the 31st of a month. Here, the 30/360 method is assumed according to the 30E/360 (ISDA) definition as given in Henrard (2013). This means that if $D1$ is the last day of the month it is changed to the 30 of that month, and if $D2$ is not the termination date and the last day of February, or if $D2$ is 31, it is changed to 30. However, these rules does not change the dates in the implementation phase of this thesis, since the dates associated with the given data do not fall on any month-ends.

Another choice that affects the day count factors is the definition of a business day. For instance, one need to apply a set of rules to handle interest period end dates that fall on non-business days. In this thesis the modified following method is applied, meaning that if an interest period ends on a non-business day, the end date is moved to the following good business day. However, if the next good business day is in the following month, then the first preceding business day is chosen. Furthermore, the end of month rule is applied, meaning that if the start date of a period is the last day of a given month, then the end date will fall on the last business day of the end month. (Henrard, 2013)

In this thesis it will be assumed that the deposits are quoted using the 30/360 method. Furthermore, the forward rate agreements are assumed to be priced using the ACT/360 method. Lastly, swaps are highly customisable contracts and therefore it will be assumed in the remainder of the thesis that the interest bearing days of the swap contracts are counted with the ACT/360 method.

5 Methodology

This section will introduce the methods used to answer the research questions. These will all be implemented using MATLAB. In order to quantify the mispricing effect for swap market participants who do not adhere to the post-crisis pricing methods, the curve structures underlying the available market quotes have to be extracted. The basic idea is that in order to price a swap one has to make an assumption of how to discount future cash flows and of the future levels of interest rates. The types of curves that correspond to the pricing of swap contracts and the aforementioned assumptions are the swap curves, discount curves, zero curves and forward rate curves. Plain vanilla interest rate swaps are quoted in terms of the fixed rate of the contract, and the swap curve simply illustrates the relationship between swap quotes and maturities. The discount curve describes the discount factors for a continuous set of maturities and is extracted in order to find out how the market discounts future cash flows. The zero curve shows the relationship between different zero rates, that are underlying the discount factor, and the corresponding maturities. Lastly, the forward rate curves describe how the market price future interest rates. For instance, the three-month forward curves that will be derived in this implementation describe the expectation of the three-month interest rate at any given time in the future. Since the above-mentioned curves are extracted from a set of market quotes, they are used in order to price swap contracts consistent with the market.

Once the underlying curves have been extracted assuming an uncollateralised and a collateralised setting (see Section 3.1 and Section 3.2 respectively), the two sets of curves can be compared in order to give an initial answer to the first research question. However, to enable conclusion beyond the inspection of these curves, forward starting swaps and off-market swaps will be priced using the derived SEK curves. For a swap contract entered into today, the pricing difference from different curve construction methods might not always be clear. But if one instead looks at forward starting contracts and swaps that are either in the money or out of the money, there might be a more significant difference in the pricing (Linderstrom and Scavenius, 2010; Nashikkar, 2011). It is therefore believed that this will enable a more elaborate answer.

The same type of curves will be used in order to answer the second research question of how the choice of collateral impacts the pricing. Whereas the curves of the collateralised and uncollateralised contracts were compared in the first research question, the curves in this setting correspond to different choices of collateral. More specifically, the case of SEK and USD as collateral currencies will be investigated for the SEK IRS. Consequently, the collateralised cross currency swap conditions outlined in Section 3.2.4 will play an instrumental role for this research question, as they will be used to determine the domestic curves when one uses a foreign currency as collateral. The derived curves will then be used to analyse the impact of the choice of collateral currency. Again, it is believed that the pricing implications from the forward starting and off-market swaps will deepen the comprehension of this impact.

The third and last of the research questions will be based on the answer of the first two. Furthermore, the results from the off-market pricing will play a crucial role, as these can be used to construct scenarios of both termination and novation of swap contracts. Through the implications from the two scenarios, the third question can be answered.

5.1 Curve Construction Method

This section will introduce the curve construction method used to generate the set of discount and forward curves underlying the market quotes. The reason why Fujii et al.'s (2010b) framework was chosen for the implementation is that it is the only research available that includes the curve construction for interest rate and cross currency swaps, both with and without the assumption of collateral agreements. Furthermore, in the review of the swap pricing literature in Section 2.4 it was made apparent that their framework is an extension to previous ones, which makes Fujii et al.'s (2010b) framework the only reasonable alternative.

In the subsequent sections the methods for deriving the curves underlying the plain vanilla interest rate swaps and cross currency swaps will be described. This will first be done without and then with collateralisation. However, before describing the procedure in each of these settings, one assumption must be described. Hereafter, it will be assumed that the payment dates of the fixed and the floating legs of the swap coincide. This is already the case of the overnight indexed swaps and the cross currency swaps. However, the plain vanilla interest rate swaps often (but not always) have a fixed leg tenor of one year and a floating rate tenor of three months. Therefore, in the case of the plain vanilla interest rate swap, the common frequency is set to three months. This assumption is for example mentioned in the formulation of the pricing framework by Fujii et al. (2010b). Furthermore, Gunnarsson (2013) suggests the usage of equal payment frequencies for the two legs in order to increase the precision of the replicated swap quotes. The most important reason behind this assumption will be made apparent for the collateralised contracts. If one were to proceed with a fixed leg tenor of one year, this would induce a scenario where the forward rates derived for a collateralised plain vanilla interest rate swap would have to be assumed to be piecewise flat, meaning that the forward rate curve would jump every fourth quarter and be constant in between. This effect is exemplified in the implementation of Gunnarsson (2013). In other words, the assumption of coinciding payment dates is not simply introduced for convenience, but to generate smooth curves.

5.1.1 Uncollateralised Plain Vanilla Interest Rate Swap

With the aforementioned assumption regarding the coinciding payment frequencies in mind, the first step of the curve construction process for the uncollateralised plain vanilla interest rate swap is to determine the short end of the discount curve. This is done with the use of deposit and FRA data, and the corresponding Eq. (4.1) and Eq. (4.2). Here, the discounting curve is built in a stepwise manner, starting with the three-month pillar and moving upwards.

Now, to ease the understanding of the following steps it is time to recall the two main equations of the uncollateralised plain vanilla interest rate swap, namely Eq. (3.1) and Eq. (3.5), here denoted as Eq. (5.1) and Eq. (5.2) respectively.

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t[L(T_{n-1}, T_n)] P_{t,T_n} \tag{5.1}$$

$$P_{t,T_N} = \frac{P_{t,T_0} - C_{t,T_N} \sum_{n=1}^{N-1} \Delta_{T_{n-1},T_n} P_{t,T_n}}{1 + C_{t,T_N} \Delta_{T_{N-1},T_N}} \tag{5.2}$$

Since the short end discount factors are now known, the next step is to generate synthetic swap quotes corresponding to these. This is simply done through a rearrangement of Eq. (5.1) to the form:

$$C_{t,T_N} = \frac{\sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t[L(T_{n-1}, T_n)] P_{t,T_n}}{\sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n}} = \frac{P_{t,T_0} - P_{t,T_N}}{\sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n}} \tag{5.3}$$

By determining short end synthetic swap quotes there is no longer any need for downward extrapolation, which is preferably avoided. Instead, it is now possible to obtain the complete set of swap quotes through interpolation. Then, the remainder of the discounting curve is determined through the direct application of Eq. (5.2).

After the discount curve has been determined up to a maturity of 30 years, the next step is to determine the forward curve. In this setting, each forward rate is determined by the relation given by Eq. (3.3). Under the absence of collateral agreements and by using Libor discounting for USD or Stibor discounting for SEK, the derived discount and forward curves can now be used to determine the prices of plain vanilla interest rate swaps and thus to replicate the given input quotes.

5.1.2 Uncollateralised Cross Currency Swap

The derivation of the curves underlying the uncollateralised cross currency swap is first done under the assumption of Libor discounting, and the consistency conditions of a SEK plain vanilla interest rate swap and a USDSEK cross currency swap. An initial step of the curve construction process is to generate quarterly quotes of the cross currency basis spread, thus matching the tenor of the SEK and USD legs of the cross currency swap. Since the lowest available maturity of the cross currency basis spread is 15 months, one could be tempted to extrapolate downwards. However, the short end of the cross currency basis spread curve is instead generated through the use of foreign exchange forwards and the discount factors derived from the plain vanilla interest rate swap framework. The first step is to convert the three and six-month USD Libor discount factors to SEK discount factors by using the foreign exchange forwards with the corresponding maturity. Then, one will have determined the three and six-month SEK discount factors under the assumption of Libor as the discount rate.

Recall the consistency conditions for the cross currency swap, Eq. (3.9) and Eq. (3.10), here denoted as Eq. (5.4) and Eq. (5.5) respectively.

$$C_{t,T_N}\sum_{n=1}^{N}\Delta_{T_{n-1},T_n}P_{t,T_n} = \sum_{n=1}^{N}\delta_{T_{n-1},T_n}E_t[L(T_{n-1},T_n)]P_{t,T_n} \tag{5.4}$$

$$N_{SEK}\left(-P_{t,T_0} + \sum_{n=1}^{N}\delta_{T_{n-1},T_n}\left(E_t[L(T_{n-1},T_n)] + b_N\right)P_{t,T_n} + P_{t,T_N}\right) =$$

$$f_x(t)\left(-P^{\$}_{t,T_0} + \sum_{n=1}^{N}\delta^{\$}_{T_{n-1},T_n}E^{\$}_t[L^{\$}(T_{n-1},T_n)]P^{\$}_{t,T_n} + P^{\$}_{t,T_N}\right) \tag{5.5}$$

Since the implementation is currently described with Libor as discounting rate, one can see that the right-hand side of Eq. (5.5) is equal to zero. By using this fact and combining Eq. (5.4) and Eq. (5.5) one can derive expression for the cross currency basis spread b_N given in Eq. (5.6).

$$b_N = \frac{P_{t,T_0} - P_{t,T_N} - C_{t,T_N}\sum_{n=1}^{N}\Delta_{T_{n-1},T_n}P_{t,T_n}}{\sum_{n=1}^{N}\delta_{T_{n-1},T_n}P_{t,T_n}} \tag{5.6}$$

Now the short end of the cross currency basis spread curve is determined for maturities of three and six months, through the use of Eq. (5.6). Then a complete set of these spreads is obtained on a quarterly interval through interpolation, thus matching the tenors of the cross currency swap's SEK and USD legs. The discounting curve is then determined sequentially by recalling Eq. (3.11), here denoted as Eq. (5.7).

$$P_{t,T_N} = \frac{P_{t,T_0} - \sum_{n=1}^{N-1}(C_{t,T_N}\Delta_{T_{n-1},T_n} + b_N\delta_{T_{n-1},T_n})P_{t,T_n}}{1 + C_{t,T_N}\Delta_{T_{N-1},T_N} + b_N\delta_{N-1,N}} \tag{5.7}$$

It is worth noting that the scarcity of swap quotes is no longer an issue here since the quotes have already been determined on a quarterly basis through the method outlined in Section 5.1.1. As a next step, the forward curve is determined by iterating through Eq. (5.4) with increasing maturities, since all is known except for the forward rates.

If the assumption regarding discounting changes to Stibor, the corresponding SEK discount curve is obviously determined directly through Eq. (5.4) and is thus already known from the steps outlined for the SEK IRS in Section 5.1.1. However, if one wishes to find the USD discounting factors consistent with the assumption of Stibor discounting, the process is slightly different. The new discount curve is then determined by recalling Eq. (3.13), here denoted as Eq. (5.8).

$$P^{\$}_{t,T_N} = \frac{P^{\$}_{t,T_0} - C^{\$}_{t,T_N}\sum_{n=1}^{N-1}\Delta^{\$}_{T_{n-1},T_n}P^{\$}_{t,T_n} + \frac{N_{SEK}}{f_x(t)}\sum_{n=1}^{N}b_N\delta_{T_{n-1},T_n}P_{t,T_n}}{1 + C^{\$}_{t,T_N}\Delta^{\$}_{T_{N-1},T_N}} \tag{5.8}$$

In Eq. (5.8) the approximation of the ratio $N_{SEK}/f_x(t) \approx 1$, is valid since the spot exchange rate (with two days of spot lag) $f_x(t)$ is only slightly larger than the SEK notional per USD N_{SEK} observed at the inception of the contract. However, one could naturally insert the actual values of the numerator and denominator, should these be available. Now, the modified USD discount factors corresponding to Stibor discounting are obtained through Eq. (5.8). Then, the condition of the USD IRS market is then used to find the USD forward rates in this scenario.

5.1.3 Collateralised Plain Vanilla Interest Rate Swap

As described before, the construction of the discount and forward curves is quite different in the collateralised scenario. The introduction of collateral disconnects the forward curve from the discount curve. In contrast to the mix of different instruments used to construct the uncollateralised discount curve, the collateralised discounting curve is derived from the overnight indexed swap quotes. Due to the aforementioned fact that the overnight indexed swaps are not quoted above ten years, the first step of the procedure is to extrapolate the overnight indexed swap quotes by assuming a constant spread to the plain vanilla interest rate swap quotes. Through interpolation of the resulting set of market and synthetic quotes, a set of yearly overnight indexed swap quotes up to 30 years is constructed. Since the payment frequencies of both legs in the overnight indexed swap are annual, one can then proceed to derive the discount factors through Eq. (3.22), here repeated as Eq. (5.9) to facilitate the reader.

$$D_{t,T_N} = \frac{D_{t,T_0} - S_{t,T_N} \sum_{n=1}^{N-1} \Delta_{T_{n-1},T_n} D_{t,T_n}}{1 + S_{t,T_N} \Delta_{T_{N-1},T_N}} \tag{5.9}$$

Before proceeding to determine the forward rates of the collateralised plain vanilla interest rate swap, the discount factors must be extended to a quarterly basis. This is done through interpolation, but not in the discount factors themselves. The interpolation is instead done in the zero rates underlying the derived discount factors, for a higher degree of accuracy and a lower level of distortion. The obtained quarterly zero rates are then transformed back into discount factors. Now, the forward curve is determined by using Eq. (3.24), which is repeated here as Eq. (5.10) for convenience.

$$C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} D_{t,T_n} = \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t^c[L(T_{n-1}, T_n)] D_{t,T_n} \tag{5.10}$$

Since the swap rates C_{t,T_N} were created on a quarterly basis in the uncollateralised setting of Section 5.1.1, everything in Eq. (5.10) is known except for the forward rates. By iterating through Eq. (5.10), letting $N = 1, 2, ..., 120$, where N indicates the number of quarters up to the final maturity, the three-month forward rates are determined, whereafter the forward curve is built. To clarify, for each step in the procedure, one equation and one unknown forward rate is added which results in a unique solution.

It was mentioned in the introduction to Section 5.1 that the assumption regarding coinciding payment frequencies in the plain vanilla interest rate swap would have an impact on the collateralised construction. This is where the choice influences the collateralised scenario. If one would not assume coinciding payment frequencies, thus assuming an annual fixed tenor versus a quarterly floating tenor, the iteration through Eq. (5.10) would be quite different. One would then have to take annual steps in the iterative process. This would result in one new equation and four new unknowns in each step, which would have to be dealt with through the assumption of a piecewise flat forward curve, meaning that the forward rate changes on a yearly basis and is constant in between. But now, since the payment frequencies of the two legs of the plain vanilla interest rate swap are assumed to coincide, the forward rates are determined uniquely on a quarterly basis through Eq. (5.10).

Now, the curves from the plain vanilla interest rate swap have been constructed using both the uncollateralised and the collateralised framework. Furthermore, the swap quotes used in the process are replicated in order to get an idea of the accuracy of the implementation. The resulting set of curves can now be compared in order to provide answers to the first research question. In order to answer the second question regarding choice of collateral currency the new set of curves must be derived through the implementation of collateralised cross currency swap framework, which is done next.

5.1.4 Collateralised Cross Currency Swap

The case of the collateralised interest rate swap in Section 5.1.3 provided the method to construct the discounting and forward curves in a single currency. This section introduces payments of different currencies and more importantly exemplify a clear case of when the collateral could be posted in a foreign currency, which will have an impact on the domestic discounting curve. The implementation outlined below will give an example of how the domestic SEK discounting curve is adjusted for a foreign collateral currency, namely USD.

Three different methods to modify the domestic discount curve to account for the foreign collateral currency were given in Section 3.2.4. The first of the three were to use swap quotes of domestic swaps with foreign collateral. Since these quotes are not available the method has to be discarded in this thesis. Another option would be to use foreign exchange forward to transform the foreign discount factors into modified domestic ones. However, since the available foreign exchange forward quotes only stretch up to a maturity of six months, this option has to be put aside as well. Furthermore, it is questionable if foreign exchange forward quotes would be liquid enough to use up to 30 years. In light of the inability to apply the first two methods, the approximation given in Eq. (3.37), repeated here as Eq. (5.11) for convenience, is the only viable option.

$$E_t[L(T_{n-1}, T_n)] \approx E_t^c[L(T_{n-1}, T_n)] \tag{5.11}$$

This approximation can then be used together with Eq. (3.34) which is reiterated here as Eq. (5.12) for the reader's convenience. Here it is assumed that $N_{SEK}/f_x(t) \approx 1$.

$$N_{SEK}\left(-P_{t,T_0}+\sum_{n=1}^{N}\delta_{n-1,n}\left(E_t[L(T_{n-1},T_n)]+b_N\right)P_{t,T_n}+P_{t,T_N}\right)=$$
$$f_x(t)\left(-P^{\$}_{t,T_0}+\sum_{n=1}^{N}\delta^{\$}_{n-1,n}E^{\$}_t[L(T_{n-1},T_n)]P^{\$}_{t,T_n}+P^{\$}_{t,T_N}\right) \tag{5.12}$$

The set of USD collateralised discount factors $\{P^{\$}_{t,T_0},...,P^{\$}_{t,T_N}\}$ and the corresponding forward rates are already known from the USD collateralised USD interest rate swap. Because of the assumption in Eq. (5.11), the only remaining unknown of Eq. (5.12) is set of USD collateralised SEK discount factors $\{P_{t,T_0},...,P_{t,T_N}\}$. After these have been determined in a sequential manner the curve construction is completed, since the approximation in Eq. (5.11) means that the corresponding forward rates are already known.

As a last step the quoted cross currency basis spreads that were used are replicated in order to get an idea of the method's accuracy.

5.2 Pricing of Additional Contracts

While the analysis of the forward and discount curves is interesting in itself, in order to make the pricing effects from different choices of pricing methods more comprehensible, a couple of different swap contracts are priced to provide additional material for the analysis.

These contracts are forward starting swaps and off-market swaps. The former contract is a swap starting at a future date. The latter is a contract that is either in the money or out of the money. For instance it could be the case that the swap started some years ago and has moved away from par due to interest rate movements. Both types of contracts are used to show that it matters how one constructs the discounting curves. Furthermore, the case of off-market swaps is also used to simulate scenarios to show the importance of a correct valuation when swap contracts are either terminated or novated.

5.2.1 Forward Starting Swaps

The importance of a correct discounting curve can be illustrated in the case of pricing forward starting swaps (Linderstrom and Scavenius, 2010; Nashikkar, 2011). A forward starting swap is simply an interest rate swap where the start date is further into the future than the spot date. For instance, a forward starting swap could have a start date five years into the future and the maturity after another ten years. The pricing is done for SEK plain vanilla interest rate swaps and is first done in the pre-crisis setting of Stibor discounting. The fixed rate is then determined by rearranging Eq. (3.1) into

$$C_{t,T_k,T_N}=\frac{\sum_{n=k+1}^{N}\delta_{T_{n-1},T_n}E_t[L(T_{n-1},T_n)]P_{t,T_n}}{\sum_{n=k+1}^{N}\Delta_{T_{n-1},T_n}P_{t,T_n}} \tag{5.13}$$

where C_{t,T_k,T_N} is the swap rate agreed upon today for a swap starting at T_k (thus with the first cash flow at time T_{k+1}) and maturing at T_N. The pricing of the forward starting swaps is done assuming maturities of ten years. Although Eq. (5.13) is first used to price uncollateralised forward starting SEK IRS, the procedure is the same for the case of the SEK and USD collateralised forward starting SEK IRS, but with the discount and forward curves corresponding to these two settings. With all three sets of forward starting swap rates determined for a number of starting dates, it is possible to draw conclusions regarding the importance of adhering to the new pricing methods as well as the impact from the use of collateral and the choice of collateral currency on pricing.

5.2.2 Off-market Swaps

Apart from the aforementioned impact of the discounting method on the pricing of forward starting swaps, Nashikkar (2011) points out the importance of a correct discounting method when valuing off-market swaps, i.e. swaps that are either in the money or out of the money. Furthermore, Fujii et al. (2010a) show that off-market swap valuations can differ depending on the choice of collateral currency. From the perspective of a fixed rate payer, in the money refers to a scenario when interest rates have risen since the inception of the contract. In contrast, a fixed rate payer is said to be out of the money when interest rates have fallen since the start of the swap. Nashikkar (2011) argues that the difference between Libor and OIS discounting can be substantial when Libor-OIS spreads are wide. Furthermore, the author states that the mispricing effect is even greater for swaps far out of or in the money.

The valuation of the off-market swaps is done by assuming a number of plain vanilla interest rate swaps started in the past, all with 20 years left to maturity today. The values of these swaps are then calculated by assuming a number of different swap rates that could have been agreed upon at the inception of the contracts. The fixed leg value as a percentage of the notional for each of the swaps is then determined by rearranging Eq. (3.1) and Eq. (3.23) into the following form:

$$\mathit{Value} = C_{t,T_N} \sum_{n=1}^{N} \Delta_{T_{n-1},T_n} P_{t,T_n} - \sum_{n=1}^{N} \delta_{T_{n-1},T_n} E_t[L(T_{n-1},T_n)] P_{t,T_n} \tag{5.14}$$

Although Eq. (5.14) represents the uncollateralised SEK IRS case, the corresponding valuations are also made using the SEK collateralised SEK IRS curves and the USD collateralised SEK IRS curves. Once the three sets of off-market values are determined, one is again able to draw conclusions regarding the importance of adhering to new pricing methods, and correctly valuing the type of collateral currency. The results are furthermore of importance when pricing swaps in the context of termination or novation of the contracts.

5.3 Interpolation Method

The term interpolation was frequently mentioned in the presentation of the pricing framework for uncollateralised and collateralised swaps in Section 3.1 and Section 3.2, as well as in the description of the curve construction method in Section 5.1. In this section the choice of interpolation method will be described in further detail.

The chosen interpolation algorithm is applied to generate missing market quotes, both in terms of swap rates and the cross currency basis spreads. Furthermore, the interpolation algorithm is used to generate continuous discount and forward curves from the corresponding discrete sets. Hagan and West (2008) outline a number of desirable features of the output that one should consider when choosing among the algorithms available. First of all, the discounting and forward curves generated should be continuous and have smooth appearances. The forward rates should be positive in order to ensure the lack of arbitrage. The continuity of the curves is important for the pricing of sensitive instruments. Furthermore, the authors state locality as another characteristic that is sought after. What this means is that if the data in one area of a set is altered, these changes should not affect the whole curve. Rather, they should only affect a local area. Lastly, Hagan and West (2008) state that the forward curve should also be stable, meaning that when inputs are altered, the maximum effect on the forward rates should not exceed a certain threshold.

The chosen interpolation algorithm is cubic splines, where one fits third order polynomials between adjacent data points. Hagan and West (2008) argue that although the interpolation method is not that local, it gives rise to smooth and stable forward curves. The property of the forward curve is a significant one. Although a linear interpolation method is easy to implement and results in visually appealing and local discount curves, the choice is a very poor one as the resulting forward curves are not smooth and instead tend to have a sawtooth-like appearance (Ametrano and Bianchetti, 2013). One could proceed with even more complex choices of interpolation algorithms, such as the monotone convex method outlined by Hagan and West (2008). However, due to the scope of this thesis such methods are discarded.

In the cubic spline method one wishes to determine the coefficients α_i, β_i, γ_i and δ_i in Eq. (5.15) where $1 \leq i \leq n-1$, between the n adjacent data points $y_1, y_2, ..., y_n$ each corresponding to a time point $t_1, t_2, ..., t_n$.

$$y_i(t) = \alpha_i + \beta_i(t - t_i) + \gamma_i(t - t_i)^2 + \delta_i(t - t_i)^3 \qquad t \in [t_i, t_{i+1}] \tag{5.15}$$

In other words, there are $4n-4$ unknowns to determine, but the number of constraints only amounts to $3n-4$. There are a number of ways to choose the additional n constraints, as discussed in Hagan and West (2006, 2008). In this thesis, the additional constraints are chosen in accordance with the natural cubic spline method, meaning that the polynomials should be twice differentiable and that the second order derivative at each of the two endpoints should be equal to zero. The implementation of this interpolation method is based on the description provided by Sauer (2006).

Apart from choosing an interpolation algorithm such as cubic splines, one also has to decide where in the curve construction algorithm to apply the interpolation as well as in what elements to interpolate. This question is related to the potential use of the synthetic instruments described in Section 4.8. As was mentioned, Ametrano and Bianchetti (2013) emphasise the fact that if one decides to interpolate directly in market quotes to obtain missing pillars, the interpolation part of the curve construction is moved to the top of the method. Another option in the treatment of the missing market quotes, would be to instead describe the discount factors corresponding to these time points in terms of the known preceding discount factors and the subsequent discount factor to be determined at a time where there exist a market quote. This method was initially applied but was later removed as it increased the complexity and more importantly severely reduced the ability to review each step of the process. Note that even if this part of the interpolation can be moved throughout the curve construction algorithm, there will always be a step where one needs to interpolate in order to obtain a continuous set of discount factors and forward rates.

The question of what elements to interpolate in might seem trivial, and in several cases it is. But in order to create a continuous set of discounting factors, there are plenty of options. Hagan and West (2006, 2008) outline a number of alternatives, namely to interpolate in the discount factors, the log of discount factors, the zero rates or in the log of zero rates. In the construction of the discount curves, the interpolation will be conducted in the zero rates, both when filling the missing pillars and when generating the continuous curve from the obtained discount factors. The motivation behind the choice is that this approach is more precise. Interpolating directly in discount factors could result in a loss or distortion of information.

5.4 Limitations

In this section, the limitations of the methodology are described. Three limitations regarding the data should be kept in mind. The first one is caused by the gaps in the data series. These have made interpolations necessary, and even extrapolation in the case of the OIS quotes. In the case of missing IRS quotes, interpolation is conducted directly in the swap quotes. The same is done with the cross currency basis spread quotes. However, the three and six-month points of the cross currency basis spread curve are constructed through the use of swap rates, discount factors, and foreign exchange forwards. This introduces the second data related problem. If there is a lack of liquidity in, for instance, the foreign exchange forwards this could cause improbable results in the determination above. In the implementation, it was observed that the FRA quotes produced short end discount factors that were not coherent with the long end factors from the swap quotes. Due to the aforementioned liquidity in the swap quotes, only two of the short end factors were determined by deposits and FRAs, after which the synthetic swap quotes were generated through interpolation. The last of the three limitations is the assumption that the cross currency swaps have constant notional amounts. However, the quotes most likely correspond to mark-to-market cross currency swaps, which could have a limited yet present effect on the results.

Two limitations that are specific for the implementation of the collateralised framework should also be pointed out. The first one is the assumption of perfect collateralisation with continuous collateral posting and no clearing threshold in the formulation of the dynamics of a collateral account. However, as described by Fujii et al. (2010b) this assumption is necessary to make the analysis feasible. Moreover, they argue that since daily adjustments becoming increasingly popular, the assumption is not too far-fetched. The second assumption concerns the derivation of USD collateralised SEK curves. Since the input data does not include USD collateralised SEK swaps or foreign exchange forward beyond six months of maturity, approximating USD collateralised SEK forward rates with SEK collateralised SEK forward rates is necessary to proceed with the implementation.

5.5 Reliability and Validity

The reliability is concerned with the lack of differences in the results from repeated studies, and tends to be relatively high for quantitative studies. By assuming a high degree of reliability, one would expect to obtain similar results if the study were to be repeated. The concept of validity is instead concerned with if the results measure the right thing. (Collis and Hussey, 2009)

In the work of this thesis, the degree of reliability and validity has been increased due to a partial methodological triangulation. Essentially two different variations of the curve construction procedure were tested. The main difference was where and how the interpolation was done for time points were no swap quotes C_{t,T_N} were available.

The first method is best outlined through a simplified example for an uncollateralised interest rate swap. Suppose first that the discount factors have already been determined up to time point T_k. Furthermore, suppose that there are no swap quotes available for the time points $T_{k+1}, T_{k+2}, ..., T_{k+l}$ and that the next available quote is for maturity T_{k+l+1}. It is then clear that Eq. (5.2) cannot be used to determine the discount factors for the time points exemplified above. Instead, one has to apply an appropriate interpolation method to determine these. The interpolation is done in the zero rates underlying each discount factor. The first step of the interpolation procedure is to express the unknown zero rates for maturities $T_{k+1}, T_{k+2}, ..., T_{k+l}$ in terms of the already known zero rates for maturities $T_1, ..., T_k$ and the yet unknown zero rate for maturity T_{k+l+1}. The discount factors can then be determined through Eq. (5.2) for maturity T_{k+l+1}. Then, $T_{k+1}, T_{k+2}, ..., T_{k+l}$ can all be determined, since they are all now expressed in terms of the now known zero rates.

The second method, and the one that is used in the actual implementation, interpolates directly in the swap quotes. As pointed out by Ametrano and Bianchetti (2013) this method is often used by brokers. Furthermore, it greatly reduces the complexity and thus facilitates the scrutinising of the implementation. Here it could be mentioned that before deciding to use the natural cubic spline version, the so-called not-a-knot end conditions were tested but discarded due to the appearance of the end sections of the resulting curves.

5.6 Legitimacy of the Output

In spite of the aforementioned methodological triangulation to improve the reliability and the validity of the results, one can still ask how to know that these results are in fact correct. First it should be noted that there is a vast amount of different choices that can be made in the curve construction, regarding for instance where and how to interpolate, with varying degrees of impact on the output. This idea is also reinforced by Ametrano and Bianchetti (2013) who describe that the curves are based on several complex choices and are subject to experience and preference. In other words, it can be argued that there is not one true curve. However, to assess the general correctness of the generated curves Ametrano and Bianchetti (2013) suggest a number of methods. Three of these are applicable to this thesis, namely market knowledge, visual inspection of the curves and repricing of the input instruments. They state that first of all, the curve constructor must have sufficient market knowledge. Secondly, they propose that visual inspection of the curves can provide a clear indication of the quality of the output. The last applied method proposed by Ametrano and Bianchetti (2013) is the aforementioned repricing of the input quotes. The results from the replication of inputs are illustrated in Section 6.3, where the maximum difference between the market quotes and replicated quotes is given. To summarise, the three methods for evaluating the output, together with the methodological triangulation mentioned in Section 5.5, are believed to constitute a sufficient output error check.

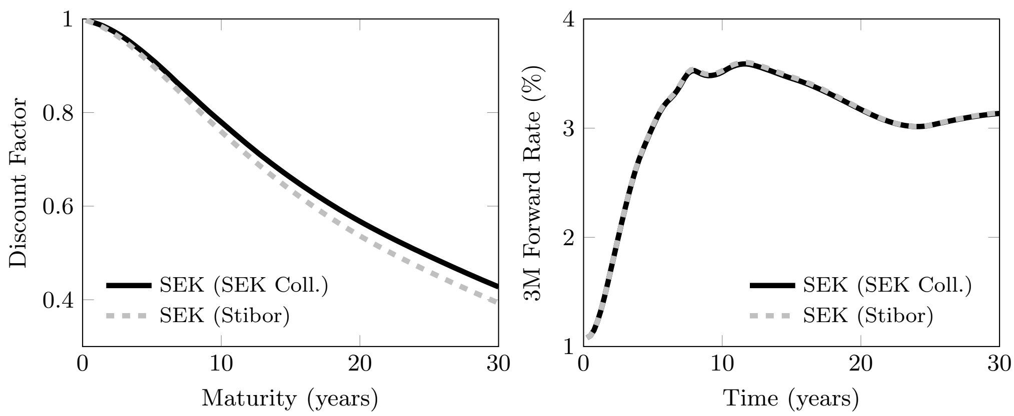
6 Results and Analysis

This section presents the results that were obtained through the implementation of the framework and the subsequent pricing. The first subsection presents the constructed discount and forward curves, both for the IRS and the CCS. The curves will be presented graphically, but tables that correspond to these figures can be found in Appendix B. The next subsection shows the results from the pricing of forward starting and off-market swaps. Based on these two subsections, the first two research questions can be answered and the foundation will be built that allows for the third research question to be discussed. To conclude the results, the third and last subsection describes the ability of the constructed curves to reprice the input quotes. This is done in order to give an idea of accuracy of the implementation.

6.1 Derived Discount and Forward Curves

6.1.1 Interest Rate Swaps

The first part of the results consists of the discount and forward curves that were generated through the implementation. The discount and forward curves that were derived from the SEK IRS quotes are shown in Fig. 6.1a and Fig. 6.1b, respectively. Both the discount and the forward curves are shown with and without collateral, in order to show the impact of collateralised contracts.



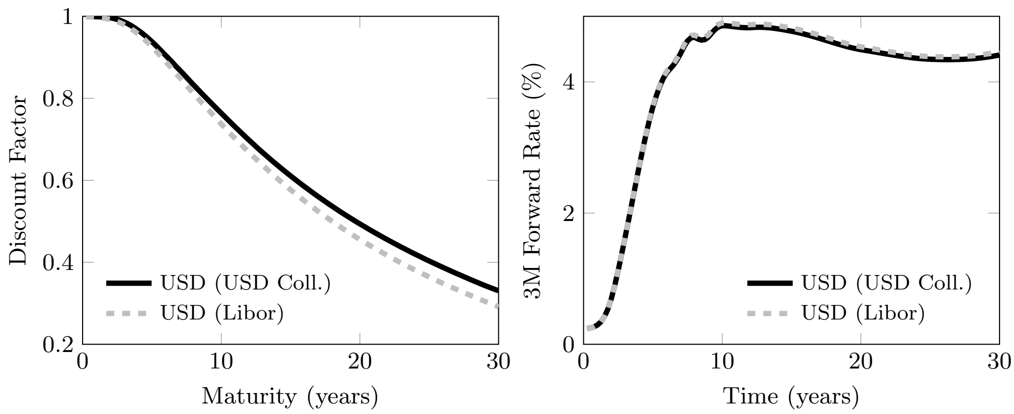
(a) SEK IRS Discount Curves

(b) SEK IRS 3M Forward Curves

Figure 6.1: The figures visualise the discount and forward curves derived from the SEK IRS quotes. Here, the label "SEK (SEK Coll.)" refers to the curves constructed under the assumption of collateralised contracts, whereas the label "SEK (Stibor)" corresponds to the case of uncollateralised contracts.

Next, Fig. 6.2a and Fig. 6.2b show the same set of curves but from the USD IRS quotes. A visual inspection of the curves of Fig. 6.1 and Fig. 6.2 indicate that while the discounting curves differ, especially in the long end, the forward curves seem to track each other more closely. The maximum distance between the SEK IRS discount curves is equal to 0.0346 and is found at 30 years. The corresponding value for the USD IRS discount curves is 0.0390 and is also found at 30 years. The SEK forward curves differ by at most 1.41 bps whereas the maximum difference is 5.32 bps for the USD forward curves.

Based on the visual inspection, it seems as if a first part of an answer to the first research question is that there is a pricing difference if one fails to account for the collateral when building the curves. But since both the uncollateralised and collateralised set of curves for USD and SEK are constructed in order to reprice the input market quotes, the pricing of spot starting par swaps is not adequate to exemplify actual pricing differences. In other words, to fully answer the first research question of the mispricing effects for a market participant who does not apply the correct pricing method, it can be argued one needs to look at the pricing of additional contracts, in order to find differences beyond the appearances of the curves. This gap is bridged through the result in the subsequent Section 6.2.



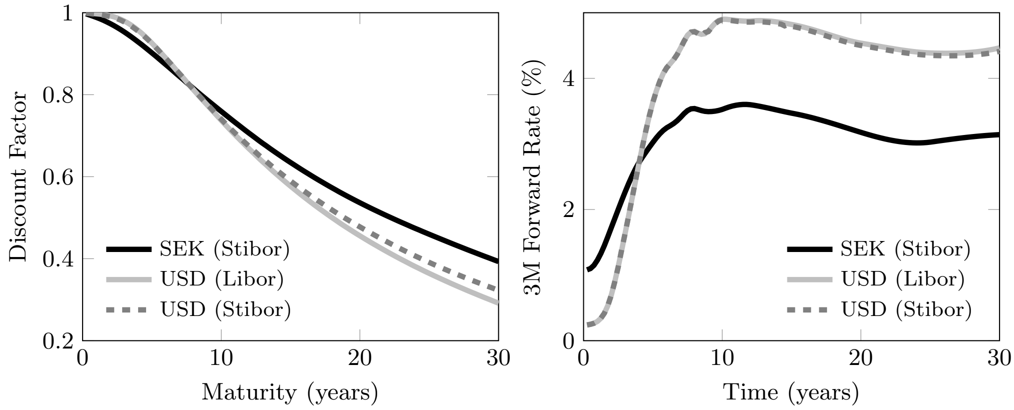
(a) USD IRS Discount Curves

(b) USD IRS Forward Curves

Figure 6.2: The figures show the discount and forward curves derived from the USD IRS quotes. In this case, "USD (USD Coll.)" refers to collateralised curves whereas "USD (Libor)" indicates that the curves are constructed without collateral.

6.1.2 Cross Currency Swaps

Now, the results from the implementation of the uncollateralised cross currency framework are shown for the USDSEK quotes. The first two figures, Fig. 6.3a and Fig. 6.3b show the discount and forward curves if one assumes Stibor as the discounting rate. As was described before, in this setting the SEK curves derived from the uncollateralised SEK IRS are left intact whilst the corresponding USD curves are modified to be consistent with the assumption of Stibor discounting. The SEK Stibor curves, USD Libor curves and the USD Stibor curves are all shown together in order to visualise the impact of the chosen discount rate. While the difference between the discounting curves is noticeable in the aforementioned figure, the maximum distance between the USD Libor and USD Stibor forward curves is 5.35 bps.

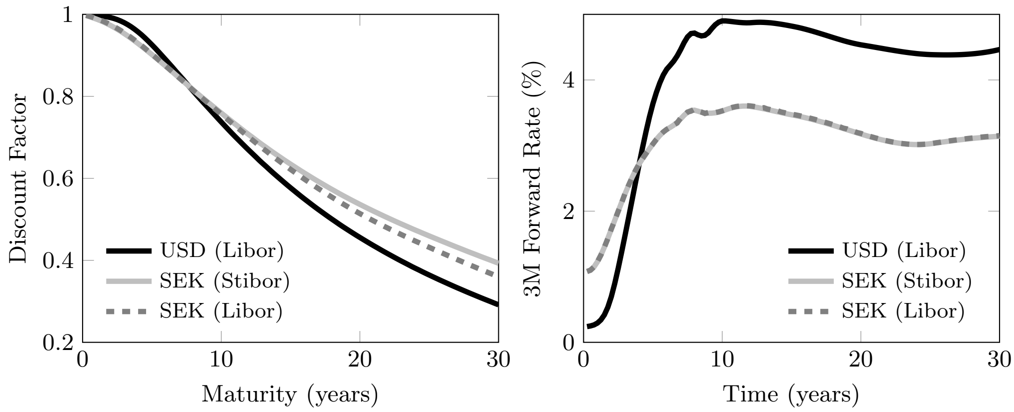


(a) CCS Discount Curves (Stibor Disc.)

(b) CCS Forward Curves (Stibor Disc.)

Figure 6.3: The two figures show the three sets of discount and forward curves. "SEK (Stibor)" and "USD (Libor)" correspond to the curves derived from the uncollateralised SEK and USD IRS. "USD (Stibor)" is derived by assuming Stibor discounting and modifying the USD curves accordingly.

In the case where Libor is assumed to be the discount rate instead of Stibor, the impact on the curves could be said to be reversed. Now, it is instead the USD curves that are left intact whilst the SEK curves are modified to be consistent with the assumption of Libor discounting and thus to price the cross currency swap consistently. The analogous discount and forward curves are shown in Fig. 6.4a and Fig. 6.4b, respectively. Again it is the case that there is a visible difference between the discount curves. The largest difference between the SEK Stibor and SEK Libor forward curves is 1.65 bps.

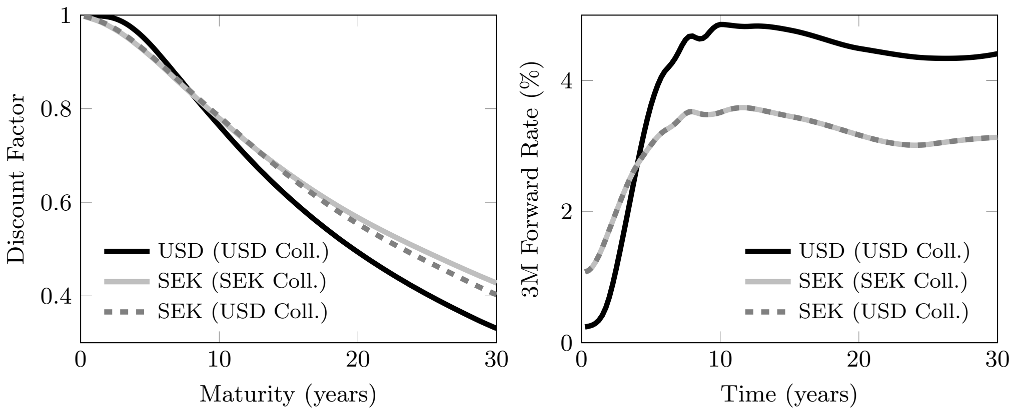


(a) CCS Discount Curves (Libor Disc.)

(b) CCS Forward Curves (Libor Disc.)

Figure 6.4: The figures show three sets of discount and forward curves. "USD (Libor)" and "SEK (Stibor)" correspond to the output from the uncollateralised USD and SEK IRS. "SEK (Libor)" is determined by assuming Libor as the discount rate.

The last set of discount and forward curves constructed from the available quotes can be used to describe a setting where a SEK contract is assumed to be collateralised with USD. Similarly to the case without collateral, USD collateral implies that the USD curves are already known and not altered whilst the SEK discount curve is modified to be consistent with the choice of USD as the collateral currency. The effect this choice has on the SEK discount curve is shown by the results from the implementation of the collateralised CCS framework, and is illustrated in Fig. 6.5a.



(a) Coll. CCS Discount Curves (USD Coll.) (b) Coll. CCS Forward Curves (USD Coll.)

Figure 6.5: The figures show the two collateralised domestic IRS curves, denoted "USD (USD Coll)" and "SEK (SEK Coll.)". Furthermore, "SEK (USD Coll.)" correspond to SEK curves with USD as the collateral currency.

Note that the USD collateralised SEK forward curve in Fig. 6.5b is determined through the approximation made in the implementation, where these forward rates are approximated by the SEK collateralised SEK forward rates. Consequently, these two forward rate curves coincide. An interesting feature of the SEK curves under USD collateral is that they do not reproduce the SEK swap quotes perfectly. This is due to the fact that the collateralised IRS condition is not used in the SEK curve construction under USD collateral, so it is clear that the USD collateralised curves should not reprice the SEK swap quotes. The differences between the SEK IRS quotes stemming from the choice of collateral currency are shown in Table 6.1.

Maturity (years)	Difference in quotes (bps) SEK (USD Coll.) - SEK (SEK Coll.)
2	-0.0126
3	-0.0062
4	0.0061
5	0.0101
6	0.0148
7	0.0294
8	0.0445
9	0.0565
10	0.0686
12	0.0692
15	0.0083
20	-0.0947
25	-0.1048
30	-0.1343

Table 6.1: The table shows the difference between the SEK IRS quotes depending on if the valuation is done assuming USD or SEK as the collateral currency. The difference is shown for the maturities of the input swap quotes.

By inspecting Fig. 6.3a and Fig. 6.4a one can see that the USD Stibor and SEK Libor discount curves end up in between the SEK Stibor and USD Libor discount curves, as one would expect. The same is true for the USD collateralised SEK discount curve, which ends up between the two curves that assume domestic collateral currencies, as shown in Fig. 6.5a. Furthermore, the uncollateralised forward curves are not significantly affected by the assumed discounting rates. The magnitude of these changes is similar to that observed in the previous comparison between the collateralised and uncollateralised curves from the IRS. Based on a visual inspection of Fig. 6.5a one can partly answer the second research question, since the choice of collateral currency seem to have an impact on the discount curve. Furthermore, the differences between the SEK IRS quotes depending on the chosen collateral currency shown in Table 6.1 also imply that the choice of collateral currency impact the pricing. But in order to provide a more vivid picture, the results from the pricing of additional contracts are needed. These are now presented in the next section.

6.2 Pricing Results

As was mentioned in the previous section, the pricing of additional contracts can provide further material to answer the research questions. This section will first present the results from the pricing of forward starting swaps, and then proceeds with the off-market swaps.

6.2.1 Forward Starting Swap Results

The pricing of forward starting plain vanilla interest rate swaps was done based on three sets of Swedish curves derived from the assumptions of Stibor discounting as well as SEK and USD collateralised discounting. Moreover, the pricing was done for swaps with ten years to maturity and for different start dates, ranging from one to 20 years into the future on a yearly basis. The resulting forward starting swap curves are shown in Fig. 6.6.

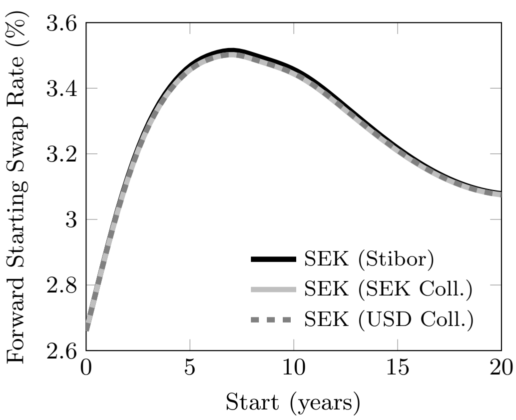


Figure 6.6: The graph shows the ten-year forward starting swap rates for a range of start dates. The label "SEK (Stibor)" corresponds to the pricing of forward starting SEK IRS without collateral. The labels "SEK (SEK Coll.)" and "SEK (USD Coll.)" correspond to the pricing of the same contract under SEK and USD collateral, respectively.

Since the observed forward starting swap curves track each other closely, these are quantified in Table 6.2 in order to clarify the differences and similarities.

Forward start	Forward Swap Rate (%)			Comparison (bps)	
(years)	Stibor	SEK Coll.	USD Coll.	Stibor - SEK Coll.	USD Coll. - SEK Coll.
1	2.91	2.91	2.91	0.25	0.06
2	3.13	3.13	3.13	0.52	0.03
3	3.30	3.29	3.29	0.77	0.02
4	3.40	3.40	3.40	0.96	0.00
5	3.47	3.46	3.46	1.11	0.00
6	3.50	3.49	3.49	1.21	0.01
7	3.51	3.50	3.50	1.28	0.02
8	3.50	3.49	3.49	1.30	0.05
9	3.48	3.47	3.47	1.30	0.08
10	3.45	3.44	3.44	1.29	0.11
11	3.41	3.40	3.40	1.24	0.14
12	3.36	3.35	3.35	1.14	0.15
13	3.31	3.30	3.30	1.02	0.16
14	3.25	3.25	3.25	0.89	0.15
15	3.21	3.20	3.20	0.76	0.14
16	3.17	3.16	3.16	0.63	0.12
17	3.13	3.13	3.13	0.51	0.09
18	3.10	3.10	3.10	0.41	0.05
19	3.09	3.08	3.08	0.34	0.02
20	3.08	3.07	3.07	0.30	-0.01

Table 6.2: The table shows ten-year SEK forward starting swap rates under the assumption of Stibor discounting as well as discounting under SEK and USD collateral, and furthermore compare the impact of collateral and collateral currency.

The forward swap rates in Table 6.2 seem to resemble each other. The difference in forward starting swap rates from the implementation with Stibor discounting and SEK collateralised discounting reaches at most 1.30 bps for a forward start in eight or nine years. To put things in perspective, for a SEK IRS with 1,000 MSEK notional starting in eight years with ten years to maturity, a failure to recognize the pricing implications of using SEK collateral and instead assuming no collateral would mean that a fixed rate payer would each year pay an excess of 130,000 SEK.

The largest difference in forward starting swap rates between SEK and USD collateralised contracts is 0.16 bps at 13 years. For a USD collateralised 1,000 MSEK notional SEK IRS starting in 13 years and with a maturity of ten years, a failure to correctly account for the USD collateral currency would mean that the fixed rate payer would pay each year 16,000 SEK more than the true forward starting swap rate suggests.

Whether or not one choses to consider these impacts large, it is clear that there are pricing differences that depend on if one uses collateral or not, and on the type of collateral that one chooses. Next, the results from the pricing of off-market swaps provide further details on how these pricing differences can be manifested.

6.2.2 Off-market Swap Results

As in the case of the forward starting swaps, the pricing of the off-market swaps is done for the SEK plain vanilla interest rate swaps. It is also assumed that the contracts have a time left to maturity of 20 years. Furthermore, the values of the swap contracts are determined from a fixed rate payer's point of view and for a range of moneyness, stretching from 200 bps out of the money to 200 bps in the money. The mid point of the interval is thus assumed to be the 20-year SEK IRS market quote of 2.99%, meaning that the interval could be translated into swap rates from 0.99% to 4.99%. Part of the results from the implementation are illustrated in Fig. 6.7, where again three methods are compared; Stibor discounting, SEK collateralised and USD collateralised discounting.

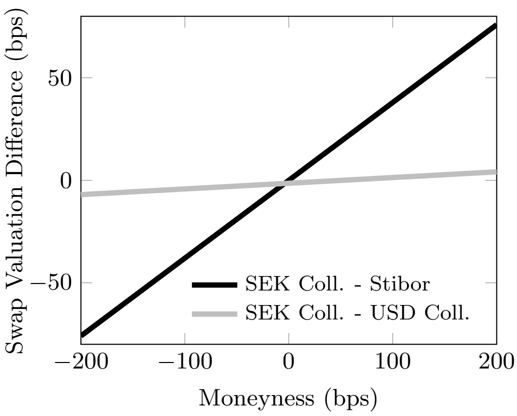


Figure 6.7: The image illustrates the differences, as basis points of the notional, between valuations of off-market swaps with 20 years left to maturity. "SEK Coll. - Stibor" is the valuation difference between the assumption of no collateral and SEK collateral. "SEK Coll. - USD Coll." is the difference depending on if one assumes SEK or USD as the collateral currency.

If one were to plot the valuations based on all three sets of curves as a function of moneyness, these would be hard to tell apart. Instead, Fig. 6.7 illustrates the differences stemming from the use of collateral and the type of collateral. To provide further details from the pricing of off-market swaps, the numerical values corresponding to the three valuations are given in Table 6.3. Furthermore, the comparisons of Fig. 6.7 are also included. One important thing to note in Table 6.3 is that the USD collateralised SEK IRS is not valued at par at zero moneyness. This is not a mistake. As previously mentioned, the moneyness interval corresponds to the quoted SEK swap rates and through Table 6.1 it was made clear that the USD collateralised SEK IRS quotes are not equal. This table layout is used as it allows for subsequent discussions and comparisons in Section 7, especially regarding research question number three.

Moneyness	Value (% of Notional)			Comparison (bps)	
(bps)	Stibor	SEK Coll.	USD Coll.	SEK Coll. - Stibor	SEK Coll. - USD Coll.
-200	-31.00	-31.76	-31.69	-75.93	-6.99
-150	-23.25	-23.82	-23.77	-56.95	-5.60
-100	-15.50	-15.88	-15.84	-37.97	-4.21
-50	-7.75	-7.94	-7.91	-18.98	-2.82
0	-0.00	-0.00	0.01	-0.00	-1.43
50	7.75	7.94	7.94	18.98	-0.04
100	15.50	15.88	15.87	37.97	1.35
150	23.25	23.82	23.80	56.95	2.74
200	31.00	31.76	31.72	75.93	4.13

Table 6.3: The table shows the values for the fixed leg of a SEK off-market IRS with 20 years left to maturity. The valuations are made assuming no collateral, SEK collateral and USD collateral. The moneyness is expressed in terms of the SEK IRS swap quotes.

The difference between the valuations under Stibor and SEK collateralised discounting shown in Table 6.3 may at first be considered small. If one for instance values a SEK IRS that is 100 bps out of the money, then the difference between the two valuations would be 37.97 bps. But for a SEK IRS with 20 years left to maturity and 1,000 MSEK notional this would mean that the values based on the two methods differ by approximately 3.80 MSEK. In other words, for contracts that are out of or in the money there seem to be price difference. Moreover, as can be seen in the table, the effect is even larger the further away one moves from the at the money swap rate. Furthermore, there are also differences between the valuations based on SEK and USD as collateral currencies, even though these are small compared to the previous case. To continue on the example of the 1,000 MSEK swap that is 100 bps out of the money, the difference of 4.21 bps between the valuations under the different collateral currencies in SEK terms would be 421,000 SEK.

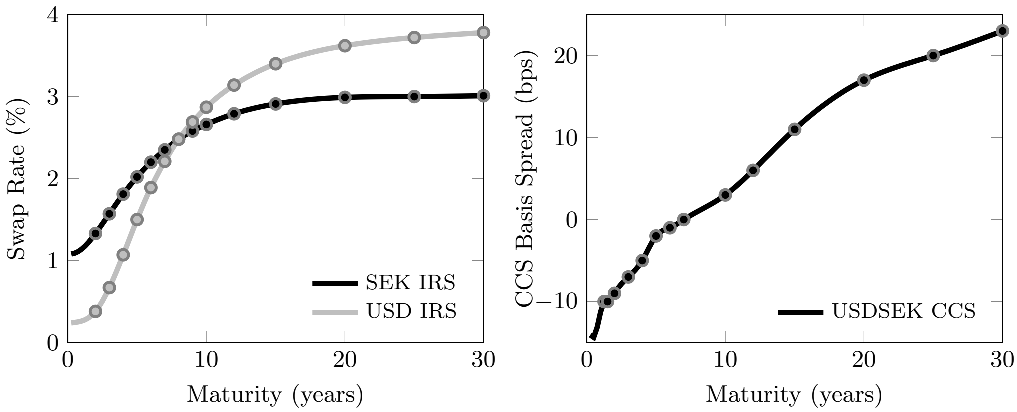
Now that the results from the forward starting and off-market swap pricing have been presented, the first research question concerning the mispricing effect stemming from the failure to account for the impact of collateral can be answered. Based on the visual comparisons in Section 6.1.1 and the results from the forward starting and off-market swap pricing seen in Table 6.2 and Table 6.3, the answer to the question is that while the inclusion of collateral has a clear impact on the discount curves, the alterations of the forward curves are not as clear. Moreover, the pricing difference is not visible when one values at the money spot starting swaps, since both the uncollateralised and SEK collateralised sets of curves are constructed to reprice the input quotes. The forward starting at the money swaps show a degree of pricing difference, and the difference is even more substantialised when one values off-market swaps and the magnitude of the impact is positively correlated with the distance from the par swap rate.

Furthermore, the implementation of the collateralised CCS in Section 6.1.2 and the results from the forward starting and off-market swap pricing together clarify how the choice of collateral currency can impact the pricing. In other words, the second research question can also be answered. The discounting of SEK cash flows under USD collateral is done using slightly higher discount factors for lower maturities and using lower discount factors for higher maturities. In other words, the new discount curve inherits properties from the USD OIS discounting curve, and consequently there is pricing difference stemming from the choice of collateral currencies. A pricing difference was also observed for the par spot pricing, as the quotes for a SEK IRS collateralised with USD was different from the corresponding quotes for an IRS with SEK as the collateral currency. However, the pricing differences are the clearest in the off-market scenario, as seen in Table 6.3.

The third and last research question asked how the results from the use and type of collateral impact the termination and novation of swap contracts. The output from the pricing of off-market swaps can be used to answer this question. However, due to the discursive nature of this question, it will be answered fully through a discussion in Section 7. The two preceding research questions will also be discussed further in the same section.

6.3 Replication of Swap Rates and Cross Currency Basis Spreads

As was mentioned in Section 5.1 and Section 5.6, in order to evaluate the applied curve construction algorithm, one can test how well it is able to reproduce the swap and cross currency basis spread quotes used as input. The replicated swap curves are shown in Fig. 6.8a where the dots represent the market quotes. The difference between the quoted and the replicated swap rates are small enough to be neglected. They deviate by no more than $1.08 \cdot 10^{-12}$ percentage points.



(a) Quoted and Replicated Swap Rates (b) Quoted and Replicated CCS Basis Spreads

Figure 6.8: The left and right figures show the replicated swap and CCS basis spread curves, respectively. The dots show the input market quotes.

The errors are also small when one compares the replicated and quoted cross currency basis spreads shown in Fig. 6.8b. The largest deviation between the quoted and replicated basis spreads occurs at the maturity of 15 months, and is no larger than $6.51 \cdot 10^{-13}$ bps. In summary, the implemented model seems to replicate the input swap rates and cross currency basis spreads well.

7 Discussion

In this chapter the obtained results will be discussed further. This is done in order to elaborate the answers to each of the three research questions:

- ◇ What is the mispricing effect for a swap market participant who adheres to pre-crisis instead of post-crisis frameworks? More specifically, what is the difference in terms of pricing with and without collateral?
- ◇ How does the choice of underlying collateral impact the pricing?
- ◇ How is the impact from the use and the type of collateral manifested when a swap contract is either novated or terminated?

These questions are treated individually in the three subsequent sections. The chapter is then concluded with a section where the sustainability of collateralisation is discussed.

7.1 Impact of Collateralisation

Based on the visual inspection of the discount curves in Fig. 6.1a and Fig. 6.2a, and the results from the pricing of forward starting and off-market swaps given in Table 6.2 and Table 6.3 it is clear that there is a difference between pricing with and without collateral. The results shown in the aforementioned figures seem reasonable, where the discount curves corresponding to collateralised contracts are positioned above the corresponding Stibor and Libor discount curves. The observed differences between the uncollateralised and collateralised discount factors are in line with the views of Ametrano and Bianchetti (2013), who argue that these two sets of factors are generally different from each other. Intuitively, the discount factors corresponding to less risky cash flows should be higher. Since the implemented collateralised pricing framework of Fujii et al.'s (2010b) assumes perfect collateralisation, these contracts are essentially risk free. On the other hand, interbank rates such as Stibor and Libor incorporate credit risk as described by Morini (2009), which explains the relative positioning of these discount curves.

The uncollateralised and collateralised forward curves shown in Fig. 6.1b and Fig. 6.2b more or less coincide. When constructing the discount and forward curves from par quotes, these are constructed in order to reprice the input. When introducing a new discounting method it is applied to both legs of the swap, which cancels out some of the change on the forward rates. Therefore it is reasonable to assume that the forward curve should not change by much in the presence of collateral. It could also be argued that the expected future interest rates for a specific currency should not be altered dramatically by how one decides to discount future cash flows. In other words, the difference between the discounting curves does not translate to a significant difference in the forward curves.

The determination of par swap quotes does not necessarily give a clear indication of pricing discrepancies, since the sets of discount and forward curves are derived to replicate the input par swap quotes. However, differences were found in the pricing of forward starting swaps, in accordance with Nashikkar (2011). Although these are also par quotes, they are given for a future start date and thus the discrepancies of the quotes could be assigned the different discounting methods and the fact that only parts of the curves that generate the same spot par quotes are used.

The difference in pricing with and without collateral is also made apparent through the results from the off-market swaps. These results are in accordance with what one should expect (Nashikkar, 2011). Since the values of the fixed and floating legs are no longer at par, the impact of the discounting method is evident. Both for in the money and out of the money swaps, the SEK OIS discounting method result in larger fluctuations of the valuations compared to the Stibor discounting. Due to the relative placement of the SEK OIS discounting curve compared to the corresponding Stibor curve, the difference in valuation is magnified since the present value of the future discrepancies is higher under the SEK OIS discounting. Moreover, since the difference between OIS and Stibor discounting is larger for higher maturities, the difference in valuation is positively correlated to the maturity of the contract.

7.2 Choice of Collateral Currency

The curves in Fig. 6.5a indicated pricing differences depending on the choice of collateral currency. These were also present in the pricing of spot spot starting, forward starting and off-market swaps.

The discount curves resulting from the uncollateralised cross currency implementation, as shown in Fig. 6.3a and Fig. 6.4a, visualise how the modified discount curves shift to settle in between the domestic Libor and Stibor discount curves. For instance, the SEK Libor discount curve is shifted towards the USD Libor discount curve when one assumes Libor as the discount rate. The same kind of observation can be made in the collateralised analogue shown in Fig. 6.5a, where the SEK discount curve under USD collateral is shifted towards the USD OIS discounting curve. These results provide the extension suggested by Ametrano and Bianchetti (2013), in terms of collateral currencies different from that of the swap. The appearances of the curves can be considered to be quite intuitive since the dependence introduced by the CCS mean that the each point of the USD collateralised SEK discount curve is a combination of the corresponding points of the parent curves.

In the implementation of the collateralised CCS, it was assumed that the unavailable SEK forward rates under USD collateral could be approximated by the available SEK forward rates under SEK collateral (see Eq. (5.11) in Section 5.1.4). The aforementioned positioning of the SEK Libor and SEK Stibor forward curves from the uncollateralised CCS offer some insight as to whether or not this assumption is indeed acceptable. Since the two curves seem to track each other closely as seen in Fig. 6.4b and with a maximum deviation of 1.65 bps the approximation suggested by Fujii et al. (2010b) could be considered reasonable. This means that the results based on the USD collateralised discount curve offers insight of how the choice of collateral currency changes the pricing.

Just as in the case with the first research question, the curves in Fig. 6.5a indicated pricing differences, as was later exemplified through the results from the spot starting, forward starting and off-market swaps. The difference of the forward swap rates in Table 6.2 is considerably lower between the choices of USD and SEK as collateral currency for a SEK IRS, than the difference between SEK collateralised and uncollateralised rates. However, the difference is non-negligible and this result is in line with the proposition of Fujii et al. (2010a). This relatively small discrepancy could be explained by several factors. First of all, the relative positioning of the SEK OIS and USD OIS discount curves matter. Furthermore, the supply and demand of these two currencies influence the CCS basis spreads. All these factors play a role in determining the positioning and shape of the SEK discount curve under the assumption of USD collateral.

A similar relationship between the results can be seen from the pricing of the off-market swaps. Table 6.3 shows that the magnitude of the relative values obtained when pricing an off-market SEK IRS and assuming USD collateral is smaller than those of the SEK collateralised SEK IRS. Again, the difference between Stibor and SEK collateralised discounting is larger than the corresponding difference between SEK and USD collateralised SEK discounting. However, it is made clear that while the error from the failure to account for a different choice of collateral currency may not be as large as failing to account for collateral in the first place, at least not in the comparison using SEK and USD, there is still pricing difference. Again, these results are in line with the claim made by Fujii et al. (2010a).

7.3 Termination and Novation

As previously mentioned, the results from the off-market swap pricing are relevant when analysing the impact of collateral and different collateral currencies. These results can be used to value contracts that are being terminated or novated and could therefore provide an answer to the third research question. For this purpose, two scenarios are created in order to illustrate this impact.

The first scenario consists of a counterparty that entered as a fixed payer into a collateralised 1,000 MSEK notional SEK IRS before the global financial crisis. This counterparty now wishes to terminate the swap that has 20 years left to maturity, is 50 bps in the money, and therefore contacts a bank to find out the cost associated with the termination. The bank could for instance respond with a certain cost involved, or perhaps offer to do it for free. In a situation like this one it is crucial for the counterparty to be able to price the contract correctly. Consider the results of the off-market pricing in Table 6.3. If the counterparty fails to value the swap according to the post-crisis framework, it could be fully satisfied with 77.5 MSEK when terminating the swap, whereas the correct amount would have been 79.4 MSEK. Thus, the potential loss from such a scenario could amount to approximately 1.9 MSEK if one does not adhere to the correct pricing method.

The second scenario consists of a counterparty who is the fixed payer in a 1,000 MSEK notional SEK collateralised SEK IRS that is about to be moved to a clearing house and where the counterparty wishes to change collateral currency to USD in the process. In order to again use Table 6.3 as an example, this swap is also assumed to have 20 years left to maturity. Just as in the case of the termination, this step requires a valuation of the current contract. Lets now assume that the current swap is 100 bps in the money. If one correctly values the SEK collateralised SEK IRS, it is worth 15.88% of the notional amount, or 158.8 MSEK. Furthermore, if the counterparty wishes to keep the fixed rate it is paying intact, the new USD collateralised SEK IRS should be valued at 15.87% of the notional amount, or 158.7 MSEK. Consequently, there are now two steps of the process where erroneous calculations could be made. In the valuation of the original swap, a failure to account for the impact of collateral could mean that value of the swap is erroneously determined to be 155.0 MSEK, and thus underestimated by approximately 3.8 MSEK. However, if one assumes that the counterparty correctly takes the usage of collateral into account, but fails to account for the change in value that accompanies the change of collateral currency, this counterparty could assume that the old and new contracts are both valued at 158.7 MSEK, thus missing out on the 135,000 SEK difference between these two stemming from the valuation difference of 1.35 bps as observed in Table 6.3.

Based on the trend where one can see that trading is shifting towards clearing houses, it is important to price contracts correctly at the stages illustrated above. In the worst of scenarios, swap dealers could otherwise profit from terminations and novations of swaps without the client's knowledge. However, this is not usually the case, since banks can even be willing to take a loss for a client in order to maintain a good relationship.

7.4 Sustainability

The concept of sustainability applies to several aspects of the financial markets. The growth of the use of collateral that has followed the recent financial crisis is both an effect of an increased awareness of counterparty credit risks and due to the aforementioned regulation. The collateralisation can itself be described as a step towards more sustainable financial markets, due to the mitigation of counterparty credit risks. However, there could potentially be some situations where the collateralisation is not as beneficial. For instance, a firm might enter into a swap agreement for hedging purposes and to cancel out other streams of cash flows. The posting and receiving of collateral might then interfere with the hedging. However, some non-financial firms can be exempted from the collateralisation if they can show that the swap for instance, is entered for hedging purposes. So generally speaking, the collateralisation of contracts can be viewed as an important step towards more sustainable financial markets. (European Securities and Markets Authority, 2013)

The main challenge lies in the ability and willingness to communicate the impact that the usage and the type collateral has on the pricing. As was shown in the results and the initial analysis in Section 6 as well as in the discussions above, the potential mispricing effect could be significant. In the worst case, dishonest swap dealers could exploit illinformed counterparties for their own benefit. However, as was mentioned in Section 7.3 this might not always be the case, since banks often focus on maintaining a good relationship with their clients.

The sustainability of the financial markets is one issue that motivated this thesis. Although a collateralised contract poses no problem in itself, there are issues arising from the fact that some market participants still use incorrect pricing methods. We hope that this study highlights the importance of using a correct curve construction and swap pricing method.

8 Conclusion

The purpose of this thesis was to apply a framework in the Swedish swap market that is able to consistently price interest rate and cross currency swaps in the presence of non-negligible cross currency basis spreads, and to investigate the pricing differences arising from the use and type of collateral.

Through the implementation of the framework proposed by Fujii et al. (2010b), no clear differences were discovered for par spot swaps in the comparison between uncollateralised and collateralised swaps. However, the ten-year forward starting interest rate swaps were found to be priced at slightly higher rates when assuming Stibor instead of SEK collateralised discounting. It is concluded that this discrepancy is mainly caused by the fact that only parts of the different sets of curves that price at spot par are used. Moreover, the results from the pricing of off-market swaps showed that disregarding the impact of collateral would cause one to consistently underestimate the change in value of a contract, whether in or out of the money. The choice of collateral currency was also shown to matter, as pricing under SEK and USD as the collateral currency yielded different results, in terms of constructed curves as well as in the pricing of spot starting, forward starting and off-market swaps. Based on the above results, two scenarios were outlined and exemplified the importance of correct pricing methods when terminating and novating swaps. From the two scenarios it is concluded that a market participant who fails to recognise the pricing implications from the usage and type of collateral could incur substantial losses.

The contribution of this thesis compared to previous research is the implementation for the interest rate and cross currency swaps using new sets of data for SEK and USD, a market not previously studied. Apart from implementing the pricing framework on a new set of data, another contribution compared to previous studies such as Gunnarsson (2013), is the simultaneous implementation without collateral and with SEK and USD as collateral currencies. Furthermore, the highlighting of the impact from the use and type of collateral was taken one step further through the pricing of SEK forward starting and off-market interest rate swaps. This provides empirical evidence for potential mispricing effects in a new market. Moreover, a contribution is also made through the generating of two concrete scenarios that monetise the impact from a potential mispricing when swaps are either terminated or novated. Lastly, the implementation was made assuming quarterly payments for both the fixed and the floating legs of the IRS. This was done in order to avoid the assumption of piecewise constant forward rates. Consequently, the output forward curves were not piecewise flat.

There are a few limitations that could potentially affect the results. One issue could be a lack of liquidity, which could distort the curves and thus affect the pricing. Moreover, since there are gaps in the data one has to rely on interpolation in order to obtain a complete set. The choice of interpolation method could influence the results, as discussed by Ametrano and Bianchetti (2013) and Hagan and West (2008). Furthermore, the extrapolation of the OIS quotes was deemed necessary to be able to compare collateralised and uncollateralised pricing for higher maturities, nevertheless differences were observed even for maturities not constructed through extrapolation. This is exemplified in the discount curves and the comparisons of swap quotes under SEK and USD as collateral. The last limitation that should be mentioned is the assumption that concern the derivation of USD collateralised SEK curves. Since the input data does not include USD collateralised SEK swaps or foreign exchange forwards beyond six months of maturity, the approximation of USD collateralised SEK forward rates with SEK collateralised SEK forward rates was necessary to proceed with the implementation.

The obtained results could be argued to lack some generalisability. A delimitation was made to focus on USD and SEK swaps, and exclusively on the SEK swaps in the pricing of additional contracts. While the differences stemming from the use and type of collateral should indeed be expected from other pairs of currencies, the direction and magnitude of these differences naturally depend on the characteristics of the markets under consideration. The aforementioned vast amount of choices that can be made throughout the implementation phase is also a limiting factor for the generalisability.

Consequently, four areas for future research have been identified. The first one could be to implement Fujii et al.'s (2010b) framework and to compare the same interest rate swaps using different currencies as collateral. This could increase the generalisability of the results on this subject. A second research area could be to compare the three methods of deriving forward and discount curves from the collateralised cross currency swap conditions. In other words, it could be interesting to compare the approximation done in this thesis with respect to forward rates, to the cases where one uses foreign exchange forwards or quotes for domestic swaps under foreign collateral. A third area for future research could be to implement the pricing framework on time series of market data in order to analyse the pricing implications in different market conditions. The fourth and last area of future research that would be interesting to investigate how the pricing differences are materialised for more exotic swaps such as step-up swaps, capped swaps and knock-out swaps.

9 Bibliography

Ametrano, F. and Bianchetti, M. (2009). Bootstrapping the illiquidity. In *Modelling Interest Rates: Advances for Derivatives Pricing*. Risk Books.

Ametrano, F. M. and Bianchetti, M. (2013). Everything you always wanted to know about multiple interest rate curve bootstrapping but were afraid to ask. *Available at SSRN 2219548*.

Avram, K., Beal, D., Gup, B. E., Kolari, J. W., and Lambert, R. (2007). *Commercial banking: the management of risk*. John Wiley & Sons.

Bianchetti, M. (2009). Two curves, one price: Pricing & hedging interest rate derivatives decoupling forwarding and discounting yield curves. *One Price: Pricing & Hedging Interest Rate Derivatives Decoupling Forwarding and Discounting Yield Curves*.

Bicksler, J. and Chen, A. H. (1986). An economic analysis of interest rate swaps. *The Journal of Finance*, 41(3):645–655.

Björk, T. (2009). *Arbitrage Theory in Continuous Time, Third Edition*. Oxford University Press.

Boenkost, W. and Schmidt, W. M. (2005). Cross currency swap valuation. *Available at SSRN 1375540*.

British Bankers' Association (2014). *Definitions*, www.bbalibor.com/explained/ /definitions, Last checked: 2014-03-08.

Chibane, M., Selvaraj, J., and Sheldon, G. (2009). Building curves on a good basis. *Available at SSRN 1394267*.

Clearly Gottlieb Steen & Hamilton LLP (2013). *Navigating Key Dodd-Frank Rules Related to the Use of Swaps by End Users*. www.cgsh.com/navigating-key-dodd-frank-rules-related-to-the-use-of-swaps-by-end-users/, Last checked: 2014-04-18.

Collis, J. and Hussey, R. (2009). *Business research: A practical guide for undergraduate and postgraduate students*. Palgrave Macmillan.

European Securities and Markets Authority (2013). *Questions and Answers: Implementation of the Regulation (EU) No 648/2012 on OTC derivatives, central counterparties and trade repositories (EMIR)*, www.esma.europa.eu/system/files/2013-1080_qa_iii_on_emir_implementation.pdf, Last checked: 2014-04-18.

Financial Stability Board (2012). *OTC Derivatives Market Reforms: Third Progress Report on Implementation*, www.financialstabilityboard.org/publications/r_120615.pdf, Last checked: 2014-04-18.

Fujii, M., Shimada, Y., and Takahashi, A. (2010a). Collateral posting and choice of collateral currency. *Available at SSRN 1601866*.

Fujii, M., Shimada, Y., and Takahashi, A. (2010b). A note on construction of multiple swap curves with and without collateral. *FSA Research Review*, 6:139–157.

Fujii, M., Shimada, Y., and Takahashi, A. (2010c). On the term structure of interest rates with basis spreads, collateral and multiple currencies. *International Workshop on Mathematical Finance at Japanese Financial Service Agency and Bank of Japan.*

Fujii, M., Shimada, Y., and Takahashi, A. (2011). A market model of interest rates with dynamic basis spreads in the presence of collateral and multiple currencies. *Wilmott*, 2011(54):61–73.

Gunnarsson, S. (2013). Curve building and swap pricing in the presence of collateral and basis spreads. Master's thesis, KTH, Mathematical Statistics.

Hagan, P. S. and West, G. (2006). Interpolation methods for curve construction. *Applied Mathematical Finance*, 13(2):89–129.

Hagan, P. S. and West, G. (2008). Methods for constructing a yield curve. *Wilmott Magazine, May*, pages 70–81.

Henrard, M. (2007). The irony in the derivatives discounting. *Available at SSRN 970509.*

Henrard, M. (2010). The irony in derivatives discounting part II: The crisis. *Wilmott Journal*, 2(6):301–316.

Henrard, M. (2013). Interest rate instruments and market conventions guide 2.0. *OpenGamma Quantitative Research*, developers.opengamma.com/quantitative-research/Interest-Rate-Instruments-and-Market-Conventions.pdf, Last checked: 2014-05-20.

Hull, J. (2012). *Options, Futures, and Other Derivatives, 8ed., Global ed.* Pearson Education.

Hull, J. and White, A. (2013). Libor vs. ois: The derivatives discounting dilemma. *Journal of Investment Management.*

International Swaps and Derivatives Association (2010). *ISDA Market Survey 2010*, www2.isda.org/attachment/Mjk5Nw==/ISDA-Market-Survey-results1987-June%202010.pdf, Last checked: 2014-05-20.

International Swaps and Derivatives Association (2013). *ISDA Margin Survey 2013*, www2.isda.org/attachment/NTY5Mw==/ISDA%20Margin%20Survey%202013 / %20FINAL.pdf, Last checked: 2014-05-20.

Ji, P. I. and In, F. (2010). The impact of the global financial crisis on the cross-currency linkage of libor–ois spreads. *Journal of International Financial Markets, Institutions and Money*, 20(5):575–589.

Linderstrom, M. D. and Scavenius, O. (2010). From curves to surfaces: How plain vanilla grew complex. *Den Danske Finansanalytikerforening*, www.finansanalytiker.dk/Files/Filer/DDF/Dokumenter/presentationer/2010/ Rentekurver/From%20curves%20to%20surfaces%20-%20to%20be%20published.pdf, Last checked: 2014-05-20.

Madigan, P. (2008). Libor under attack. *Risk*, 21(6):73.

Mercurio, F. (2009). Interest rates and the credit crunch: new formulas and market models. *Bloomberg portfolio research paper*, (2010-01).

Morini, M. (2009). Solving the puzzle in the interest rate market. *Available at SSRN 1506046*.

Nashikkar, A. (2011). *Understanding OIS discounting*, Barclays Capital Interest Rate Strategy, www.fgfoa.org/Assets/Files/Alfred_Mukunya_handout.pdf, Last checked: 2014-05-20.

Piterbarg, V. (2010). Funding beyond discounting: Collateral agreements and derivatives pricing. *Risk*, 23(2):97–102.

Sauer, T. (2006). *Numerical Analysis*. Pearson Education.

Sveriges Riksbank (2013). *The Riksbank's survey of the turnover in the foreign exchange and fixed-income markets in Sweden.* www.riksbank.se, Last checked: 2014-05-19.

Swedish Bankers' Association (2013). *Ramfverk för Stibor*, www.swedishbankers.se/web/bfmm.nsf/lupgraphics/11312Stibor_Svensk.pdf/$file/11312Stibor_Svensk.pdf, Last checked: 2014-03-08.

Taylor, J. B. and Williams, J. C. (2009). A black swan in the money market. *American Economic Journal: Macroeconomics*, 1(1):58–83.

Wood, D. (2009). The reality of risk-free. *Risk*, 22(7):24–26.

Appendix A Pricing of Collateralised Derivatives

In order to determine the process of the collateral account as in Fujii et al. (2010b), let $V(t)$ be value of the collateral account at time t, $c(t)$ the collateral rate, $r(t)$ the risk free rate, $h(t)$ the value of a derivative at time t and $a(t)$ the number of positions in the aforementioned derivative, then the dynamics of a collateral account with continuous posting and perfect collateralisation can be described by the following stochastic differential equation:

$$dV(s) = (r(s) - c(s))V(s)ds + a(s)dh(s) \tag{A.1}$$

where it is also assumed that the collateralisation is made continuously and without any clearing threshold. Eq. (A.1) can be interpreted as follows: The change in value of the collateral account depends on the interest differential earned on the posted collateral over time as well as the change in the value of the $a(s)$ underlying derivatives. By applying Proposition 5.3 (Björk, 2009, p. 70) one can see that the solution to the stochastic differential equation in Eq. (A.1) is given by

$$V(T) = e^{\int_t^T (r(u)-c(u))du}V(t) + \int_t^T e^{\int_s^T (r(u)-c(u))du}a(s)dh(s) \tag{A.2}$$

By adopting a trading strategy with $V(t) = h(t)$ and $a(s) = e^{\int_t^s (r(u)-c(u))du}$ as in Fujii et al. (2010b) one will find that Eq. (A.2) reduces to

$$V(T) = e^{\int_t^T (r(s)-c(s))ds}h(T) \tag{A.3}$$

From Eq. (A.3) one can then see that the present value of the derivative given the information at time t and with the expectation taken using the money market account as numeraire is

$$h(t) = E_t\left[e^{-\int_t^T c(s)ds}h(T)\right] \tag{A.4}$$

Now, if one instead considers a collateral account where the collateral is posted in a foreign currency, the corresponding stochastic differential equation is

$$dV^f(s) = (r^f(s) - c^f(s))V^f(s)ds + a(s)d\left(\frac{h(s)}{f_x(s)}\right) \tag{A.5}$$

where the superscript f indicates the foreign currency and $f_x(s)$ is the exchange rate at time s. By applying the same proposition as before, one will arrive at

$$V^f(T) = e^{\int_t^T (r^f(u)-c^f(u))du}V^f(t) + \int_t^T e^{\int_s^T (r^f(u)-c^f(u))du}a(s)d\left(\frac{h(s)}{f_x(s)}\right) \tag{A.6}$$

The trading strategy adopted in Fujii et al. (2010b) is now $V^f(t) = \frac{h(s)}{f_x(s)}$ and $a(s) = e^{\int_t^s (r^f(u)-c^f(u))du}$ under which Eq. (A.6) can be rewritten as

$$V^f(T) = e^{\int_t^T (r^f(s)-c^f(s))ds}\frac{h(T)}{f_x(T)} \tag{A.7}$$

and thus one can find that the present value of the derivative given the information at time t and expressed in the domestic currency is now

$$h(t) = E_t \left[e^{-\int_t^T r(s)ds} e^{\int_t^T (r^f(s) - c^f(s))ds} h(T) \right] \tag{A.8}$$

Appendix B Additional Tables

Maturity (years)	Discount Factors SEK (SEK Coll.)	SEK (Stibor)
1	0.99	0.99
2	0.98	0.97
3	0.96	0.95
4	0.94	0.93
5	0.91	0.90
6	0.89	0.87
7	0.86	0.84
8	0.83	0.81
9	0.81	0.79
10	0.78	0.76
11	0.75	0.73
12	0.73	0.71
13	0.71	0.68
14	0.68	0.66
15	0.66	0.63
16	0.64	0.61
17	0.62	0.59
18	0.60	0.57
19	0.58	0.55
20	0.57	0.54
21	0.55	0.52
22	0.54	0.50
23	0.52	0.49
24	0.51	0.47
25	0.49	0.46
26	0.48	0.45
27	0.47	0.43
28	0.45	0.42
29	0.44	0.41
30	0.43	0.39

(a) SEK IRS Discount Factors

Time (years)	3M Forward Rates (%) SEK (SEK Coll.)	SEK (Stibor)
1	1.23	1.23
2	1.72	1.72
3	2.27	2.27
4	2.71	2.72
5	3.02	3.02
6	3.24	3.25
7	3.40	3.41
8	3.53	3.54
9	3.48	3.49
10	3.51	3.53
11	3.58	3.59
12	3.58	3.60
13	3.55	3.56
14	3.50	3.51
15	3.46	3.47
16	3.41	3.42
17	3.36	3.37
18	3.30	3.31
19	3.23	3.24
20	3.17	3.18
21	3.11	3.11
22	3.06	3.06
23	3.03	3.03
24	3.01	3.02
25	3.03	3.03
26	3.05	3.06
27	3.08	3.08
28	3.10	3.11
29	3.12	3.13
30	3.13	3.14

(b) SEK IRS Forward Rates

Table B.1: The tables show the discount factors and three-month forward rates from Fig. 6.1 on a yearly basis. The label "SEK (SEK Coll.)" refers to the output under the assumption of collateralised contracts, whereas the label "SEK (Stibor)" corresponds to the case of uncollateralised contracts.

Maturity	Discount Factors	
(years)	USD (USD Coll.)	USD (Libor)
1	1.00	1.00
2	1.00	0.99
3	0.99	0.98
4	0.97	0.96
5	0.94	0.93
6	0.90	0.89
7	0.87	0.85
8	0.83	0.81
9	0.80	0.77
10	0.76	0.74
11	0.73	0.70
12	0.70	0.67
13	0.67	0.64
14	0.64	0.61
15	0.61	0.58
16	0.58	0.55
17	0.56	0.52
18	0.54	0.50
19	0.51	0.48
20	0.49	0.46
21	0.47	0.44
22	0.45	0.42
23	0.44	0.40
24	0.42	0.38
25	0.40	0.36
26	0.39	0.35
27	0.37	0.33
28	0.36	0.32
29	0.34	0.31
30	0.33	0.29

(a) USD IRS Discount Factors

Time	3M Forward Rates (%)	
(years)	USD (USD Coll.)	USD (Libor)
1	0.29	0.29
2	0.69	0.69
3	1.64	1.64
4	2.70	2.71
5	3.62	3.64
6	4.14	4.16
7	4.43	4.46
8	4.68	4.72
9	4.68	4.72
10	4.86	4.90
11	4.84	4.88
12	4.83	4.87
13	4.83	4.88
14	4.81	4.86
15	4.77	4.82
16	4.72	4.77
17	4.66	4.71
18	4.60	4.65
19	4.54	4.58
20	4.49	4.54
21	4.46	4.50
22	4.42	4.46
23	4.39	4.43
24	4.36	4.40
25	4.35	4.39
26	4.34	4.38
27	4.34	4.38
28	4.35	4.40
29	4.38	4.42
30	4.41	4.46

(b) USD IRS Forward Rates

Table B.2: The tables show the discount factors and three-month forward rates from Fig. 6.2 on a yearly basis. The label "USD (USD Coll.)" refers to the output under the assumption of collateralised contracts, whereas the label "USD (Libor)" corresponds to the case of uncollateralised contracts.

	Discount Factors		
Maturity	SEK	USD	USD
(years)	(Stibor)	(Libor)	(Stibor)
1	0.99	1.00	1.00
2	0.97	0.99	0.99
3	0.95	0.98	0.98
4	0.93	0.96	0.96
5	0.90	0.93	0.92
6	0.87	0.89	0.89
7	0.84	0.85	0.85
8	0.81	0.81	0.81
9	0.79	0.77	0.78
10	0.76	0.74	0.74
11	0.73	0.70	0.71
12	0.71	0.67	0.67
13	0.68	0.64	0.64
14	0.66	0.61	0.62
15	0.63	0.58	0.59
16	0.61	0.55	0.56
17	0.59	0.52	0.54
18	0.57	0.50	0.52
19	0.55	0.48	0.50
20	0.54	0.46	0.48
21	0.52	0.44	0.46
22	0.50	0.42	0.44
23	0.49	0.40	0.42
24	0.47	0.38	0.41
25	0.46	0.36	0.39
26	0.45	0.35	0.38
27	0.43	0.33	0.36
28	0.42	0.32	0.35
29	0.41	0.31	0.34
30	0.39	0.29	0.32

(a) CCS Discount Factors (Stibor Disc.)

	3M Forward Rates (%)		
Time	SEK	USD	USD
(years)	(Stibor)	(Libor)	(Stibor)
1	1.23	0.29	0.29
2	1.72	0.69	0.70
3	2.27	1.64	1.64
4	2.72	2.71	2.71
5	3.02	3.64	3.64
6	3.25	4.16	4.16
7	3.41	4.46	4.46
8	3.54	4.72	4.71
9	3.49	4.72	4.71
10	3.53	4.90	4.89
11	3.59	4.88	4.87
12	3.60	4.87	4.86
13	3.56	4.88	4.86
14	3.51	4.86	4.83
15	3.47	4.82	4.79
16	3.42	4.77	4.74
17	3.37	4.71	4.68
18	3.31	4.65	4.61
19	3.24	4.58	4.55
20	3.18	4.54	4.50
21	3.11	4.50	4.46
22	3.06	4.46	4.43
23	3.03	4.43	4.39
24	3.02	4.40	4.37
25	3.03	4.39	4.35
26	3.06	4.38	4.34
27	3.08	4.38	4.34
28	3.11	4.40	4.35
29	3.13	4.42	4.37
30	3.14	4.46	4.41

(b) CCS Forward Rates (Stibor Disc.)

Table B.3: The tables show the three sets of discount factors and forward rates. "SEK (Stibor)" and "USD (Libor)" correspond to the output from the uncollateralised SEK and USD IRS. "USD (Stibor)" is derived by assuming Stibor discounting and modifying the USD discount factors and forward rates accordingly.

	Discount Factors		
Maturity	USD	SEK	SEK
(years)	(Libor)	(Stibor)	(Libor)
1	1.00	0.99	0.99
2	0.99	0.97	0.98
3	0.98	0.95	0.96
4	0.96	0.93	0.93
5	0.93	0.90	0.90
6	0.89	0.87	0.87
7	0.85	0.84	0.84
8	0.81	0.81	0.81
9	0.77	0.79	0.78
10	0.74	0.76	0.76
11	0.70	0.73	0.73
12	0.67	0.71	0.70
13	0.64	0.68	0.67
14	0.61	0.66	0.65
15	0.58	0.63	0.62
16	0.55	0.61	0.60
17	0.52	0.59	0.58
18	0.50	0.57	0.55
19	0.48	0.55	0.53
20	0.46	0.54	0.51
21	0.44	0.52	0.50
22	0.42	0.50	0.48
23	0.40	0.49	0.46
24	0.38	0.47	0.45
25	0.36	0.46	0.43
26	0.35	0.45	0.42
27	0.33	0.43	0.40
28	0.32	0.42	0.39
29	0.31	0.41	0.37
30	0.29	0.39	0.36

(a) CCS Discount Factors (Libor Disc.)

	3M Forward Rates (%)		
Time	USD	SEK	SEK
(years)	(Libor)	(Stibor)	(Libor)
1	0.29	1.23	1.23
2	0.69	1.72	1.73
3	1.64	2.27	2.28
4	2.71	2.72	2.72
5	3.64	3.02	3.02
6	4.16	3.25	3.25
7	4.46	3.41	3.42
8	4.72	3.54	3.55
9	4.72	3.49	3.51
10	4.90	3.53	3.53
11	4.88	3.59	3.59
12	4.87	3.60	3.60
13	4.88	3.56	3.58
14	4.86	3.51	3.53
15	4.82	3.47	3.48
16	4.77	3.42	3.43
17	4.71	3.37	3.38
18	4.65	3.31	3.32
19	4.58	3.24	3.25
20	4.54	3.18	3.19
21	4.50	3.11	3.12
22	4.46	3.06	3.07
23	4.43	3.03	3.03
24	4.40	3.02	3.02
25	4.39	3.03	3.03
26	4.38	3.06	3.06
27	4.38	3.08	3.09
28	4.40	3.11	3.11
29	4.42	3.13	3.14
30	4.46	3.14	3.15

(b) CCS Forward Rates (Libor Disc.)

Table B.4: The tables show the three sets of discount factors and forward rates. "USD (Libor)" and "SEK (Stibor)" correspond to the output from the uncollateralised USD and SEK IRS. "SEK (Libor)" is determined by assuming Libor as the discount rate.

	Discount Factors		
Maturity (years)	USD (USD Coll.)	SEK (SEK Coll.)	SEK (USD Coll.)
1	1.00	0.99	0.99
2	1.00	0.98	0.98
3	0.99	0.96	0.96
4	0.97	0.94	0.94
5	0.94	0.91	0.91
6	0.90	0.89	0.89
7	0.87	0.86	0.86
8	0.83	0.83	0.84
9	0.80	0.81	0.81
10	0.76	0.78	0.78
11	0.73	0.75	0.76
12	0.70	0.73	0.73
13	0.67	0.71	0.70
14	0.64	0.68	0.68
15	0.61	0.66	0.66
16	0.58	0.64	0.63
17	0.56	0.62	0.61
18	0.54	0.60	0.59
19	0.51	0.58	0.57
20	0.49	0.57	0.55
21	0.47	0.55	0.54
22	0.45	0.54	0.52
23	0.44	0.52	0.50
24	0.42	0.51	0.49
25	0.40	0.49	0.47
26	0.39	0.48	0.46
27	0.37	0.47	0.44
28	0.36	0.45	0.43
29	0.34	0.44	0.42
30	0.33	0.43	0.40

Table B.5: The table shows three sets of Discount Factors under collatereral. "USD (USD Coll)" and "SEK (SEK Coll.)" refer to to the case where the collateral currency coincides with that of the contract, whereas "SEK (USD Coll.)" correspond to SEK Discount Factors with USD as the collateral currency. Note that the Forward Rates are left out since these coincide with the rates under collateral from Table B.1 and Table B.2, due to the aforementioned approximation.