ANALYSIS

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Liquidity stress test shows that Kronos is resilient

- In Kronos, settlement of payments is centred on two large participants whose failure may substantially increase the other participants' liquidity requirements.
- The significance of the unsecured money market for liquidity in the system was reduced from 2009 to 2018, and the participants are not affected to any notable degree by a reduction of their available intraday credit.
- The participants have ample available liquidity, so the impact of an increase in their liquidity requirements on the settlement of payments in all the simulated scenarios is limited and can be mitigated by means of Kronos' contingency procedures.

Kronos is Danmarks Nationalbank's payment system for large, time-critical payments and it is at the core of the Danish financial infrastructure. The analysis assesses the resilience of the system, measured as the change in the participants' liquidity requirements and their ability to settle their payments on time when the system is exposed to stress in three different scenarios: 1. A large participant is unable to submit payments for a whole day; 2. the money market is unavailable; and 3. participants' access to intraday credit is reduced.

Introduction to Kronos

The Kronos payment system handles the final exchange of liquidity for all payments in Danish kroner. If one bank needs to transfer funds electronically to another bank, payment is made in Kronos by debiting the former bank's account while crediting the latter bank's account at Danmarks Nationalbank. Kronos is commonly called the online banking service for the banks.

In August 2018, Danmarks Nationalbank migrated to a new system, Kronos2. This analysis is based on data from Kronos. Since then, the participants' behaviour has changed only slightly in terms of the number, value and timing of their interbank payments. Liquidity in the system remains ample, and monetary policy rates are the same as in 2016-2017.

Kronos is a real-time gross settlement system, RTGS, i.e. payments in the system are settled in real time (immediately) without netting[1] in central bank money. Kronos serves three main objectives as a platform for 1. large, time-critical interbank payments, including payments on behalf of the participants' customers; 2. monetary policy operations; and 3. final settlement of obligations in ancillary systems. The primary ancillary systems include the Sumclearing, the Intradagclearing and the Straksclearing for retail payments, the VP settlement system and the TARGET2-Securities for securities settlement and CLS for foreign exchange settlement.[2]

The system is used by 88 direct participants, the large Danish banks submitting and receiving the majority of payments in terms of both number and value. Payments averaging kr. 144 billion were settled daily in Kronos in 2018, corresponding to 6.5 per cent of Denmark's GDP.[3] Kronos is a critical part of the Danish financial infrastructure and can be characterised as a systemically important payment system, SIPS. With this stress test, Kronos complies with the international oversight standards recommending that the liquidity risks of the system should be regularly evaluated, including through stress testing.[4]

Liquidity risk in Kronos

Kronos is exposed to several types of risk, including operational risk, legal risk and reputational risk, but this stress test focuses solely on liquidity risk. For example, technical failures or cyberattacks on the IT platform of the system itself are not included in the analysis.

Liquidity risk is the risk of the participants in the system not having sufficient liquidity to execute their payments in a timely manner. This may create further problems for other participants' ability to pay when they base their liquidity management on an expected flow of payments received. The liquidity problems of one participant may thus spread throughout the system through contagion to other participants. Danmarks Nationalbank incurs no liquidity risk, as all payments between the participants in an RTGS system are immediate, final and irrevocable.

The stress test examines the resilience of the system to shocks to the participants' liquidity under extreme but plausible scenarios. The system is taken to mean Kronos itself plus its participants and transfers to accounts for its ancillary systems.

If appropriate, a stress test analysis may result in specific change proposals for both the participants' behaviour and/or the system design, including queuing features, collateral basis and monetary policy day. In this analysis, Kronos is deemed to be resilient to the liquidity shocks inflicted on the system, so the analysis does not give cause for change proposals.

The analysis initially sets out the methodology and scenarios of the stress test, including its critical assumptions and related sources of error. It then

1 Netting adds up the amounts due between the parties and compiles the payment flow into as few transactions as possible.

2 For more details on Kronos, see e.g. Danmarks Nationalbank (2016).

3 This is exclusive of internal transfers between the participants' own settlement accounts and transfers to T2S.

4 See CPSS-IOSCO (2012) under Principle 7 on liquidity risk.

reviews the results of the test simulations and subsequently discusses them. Finally, proposals are made for future analysis.

Methodology and stress scenarios

Data and methodology
The analysis comprises data from Kronos, including all the actual transactions settled during the opening hours of the system between 7:00 am and 3:30 pm on each business day from 2 January 2007 to 3 August 2018.[5] In addition, information about participants' balance sheets and their available intraday credit for traditional pledging of securities is used.

The data is loaded into a simulator (BoF-PSS2[6]), in which payments are settled the same way as in Kronos: the simulator is set up to mimic the set-up and functions of the real system as much as possible.

The stress scenarios are implemented by changing input data and then executing the payments under otherwise unchanged conditions. This ensures a fair test of the impact of the scenarios on the resilience of the system. The impact is evaluated on the basis of five indicators calculated on the output data generated by the simulator.

If the input data is unaffected, the simulator should to the best of its ability settle all the payments as they were actually made. Such a *benchmark* simulation is run for the entire period and is the basis of the assessment of the impact of the stress scenarios on the system. In this way, the simulator's simplifications of reality apply to both the stress scenarios and their basis for comparison.

Liquidity sources and checks for adequate cover
Overall, a participant can use three liquidity sources to settle its payments:

- Current account balance at the start of the day
- Payments received during the day
- Access to intraday credit from Danmarks Nationalbank during the day.

When a participant *submits* a payment, Kronos performs a check for adequate cover. The amount must be lower than or equal to the sum of the participant's current account balance and available intraday credit in order for the payment to be *settled*. In other words, settlement requires that the participant's *available liquidity* is sufficient to cover the participant's *liquidity requirement*.

If the check for adequate cover fails, the payment is queued and will not be settled until the participant has sufficient liquidity to meet the requirement. If several payments are queued, the payments will be settled according to the FIFO principle, i.e. the earliest submitted payment in the queue is sought to be settled before the second earliest payment in the queue and so forth.[7] Payments that are still queued when Kronos closes at 3:30 pm will remain *unsettled*.

Table 1 shows an example of a simple payment flow of 10 payments between three participants: banks A, B and C. Under *Benchmark* and each of the three scenarios, three columns are showing the amount of the payment, the payer's current account balance *before* payment and the payer's access to intraday credit. A negative balance means that the participant draws on its credit.

Under Benchmark, the check for adequate cover is met for all 10 payments, and they are settled in a

5 This period was selected so that it runs from before the financial crisis in 2008 until the introduction of Kronos2 and before the related data break.

6 *Bank of Finland's Payment System Simulator 2* is a payment simulator developed by the Bank of Finland. Read more about it at (*link*).

7 Participants can also activate a bypass feature whereby the first payment in the queue is bypassed if it cannot be settled. The next payment in the queue does not await the necessary liquidity, but is sought to be settled immediately, and so forth. The bypass feature is included in the simulations. In addition, Danmarks Nationalbank can activate an algorithm that resolves gridlocks in the system (see Bech and Soramäki, 2001). The algorithm is excluded from the simulations, as modelling of Danmarks Nationalbank's (and the participants') behaviour is beyond the scope of this analysis.

Impact of the stress scenarios on a simple payment flow between three participants Table 1

			Benchmark			Remove Participant (RP)			Money Market (MM)			Intraday Credit (IC)		
Time	From	To	Amount	Balance	Credit	Amount	Balance	Credit	Amount	Balance	Credit	Amount	Balance	Credit
07:30	Bank A	Bank B	10	0	60 ✓	~~10~~	0	60 ÷	~~10~~	0	60 ÷	10	0	45 ✓
08:17	Bank B	Bank A	20	40	0 ✓	20	30	0 ✓	20	30	0 ✓	20	40	0 ✓
09:01	Bank A	Bank C	40	10	60 ✓	~~40~~	20	60 ÷	40	20	60 ✓	40	10	45 ✓
09:37	Bank C	Bank B	20	40	32 ✓	20	0	32 ✓	20	40	32 ✓	20	40	24 ✓
10:02	Bank B	Bank C	25	40	0 ✓	25	30	0 ✓	~~25~~	30	0 ÷	25	40	0 ✓
11:04	Bank C	Bank A	50	45	32 ✓	50	5	32 ✗	50	20	32 ✓	50	45	24 ✓
12:15	Bank C	Bank A	20	-5	32 ✓	20	5	32 ✓	20	-30	32 ✗	20	-5	24 ✗
13:53	Bank A	Bank B	50	40	60 ✓	~~50~~	40	60 ÷	50	30	60 ✓	50	20	45 ✓
14:11	Bank A	Bank C	30	-10	60 ✓	~~30~~	40	60 ÷	30	-20	60 ✓	30	-30	45 ✗
15:07	Bank B	Bank C	30	65	0 ✓	30	5	0 ✗	30	80	0 ✓	30	65	0 ✓

Note: ✓: Settled; ÷: Not submitted; ✗: Unsettled. In the RP scenario, all payments submitted from Bank A are removed. In the MM scenario, two payments are identified as money market transactions and removed. In the IC scenario, the participants' available intraday credit is reduced by 25 per cent.
Source: Own work.

timely manner. No payments are queued or remain unsettled.

Remove Participant (RP) scenario: one large participant is unable to submit payments for a whole day

In the event of a major operational incident such as an extensive cyberattack or IT failure, a participant may be unable to submit payments in Kronos.[8] The first scenario (RP) mimics this situation by removing from the settlement all payments from a single large participant over a whole business day.

Table 1 illustrates the impact on the simple payment flow of Bank A's inability to submit its payments: Bank C does not receive the expected liquidity from Bank A at 9:01 am and therefore does not have sufficient liquidity to settle its payment at 11:04 am. The same applies to Bank B's payment at 3:07 pm. Both payments are queued and remain unsettled at the end of the business day.

Bank A is still receiving payments from the other participants and is called a *liquidity sink*, as the liquidity received is not reused in the system on the same day.

The *direct effect* of a scenario is defined as

$$\frac{\textit{Value of non-submitted payments in the scenario}}{\textit{Value of submitted payments in the benchmark}}$$

In the example in Table 1, the direct effect of removing Bank A is

130/295 = 44.1 per cent.

8 If a participant has access to neither SWIFT nor the Kronos terminal. Note that the *participant* can be exposed to an operational incident, while operational risk in *Kronos* is excluded from the analysis.

The *indirect effect* of a scenario is defined as

$$\frac{\textit{Value of unsettled payments in the scenario}}{\textit{Value of submitted payments in the scenario}}$$

The indirect effect of removing Bank A is

$$80/165 = 27.1 \text{ per cent.}$$

The direct and indirect effects can be regarded as measures of the first-order and multi-order effects of a scenario. In the example in Table 1, there is only a first-order and a second-order effect of the RP scenario, because both unsettled payments follow directly from lack of liquidity from Bank A. In reality, removing one large participant may result in unsettled payments for another participant, which in turn will affect the liquidity of a third participant further along in the payment chain, and so forth. All these unsettled payments are included in the numerator of the indirect effect, which is calculated for each of the simulations below.

The *multiplier effect* of a scenario is defined as

$$\frac{\textit{Value of unsettled payments in the scenario}}{\textit{Value of non-submitted payments in the scenario}}$$

The multiplier effect of removing Bank A is

$$80/130 = 61.5 \text{ per cent.}$$

For each krone removed from the system, payments for a further kr. 0.62 will not be settled. The multiplier effect indicates whether the participant removed plays a particularly important role for the payment system relative to its size. This typically applies to large and medium-sized banks acting as links for smaller participants to the rest of the system.

***Money Market* (MM) scenario: the money market is unavailable for a whole day**

During the financial crisis in the autumn of 2008, the unsecured money market froze. Turnover declined and the spread between the secured and unsecured money market interest rates widened considerably. The situation was particularly dire in dollars, but the Danish money market in kroner was also affected. The consequence for the krone market was that participants with excess liquidity increasingly chose to place it with Danmarks Nationalbank rather than relending it. As a result, participants with a funding requirement had to borrow from Danmarks Nationalbank instead of in the money market.[9]

The second scenario (MM) mimics this situation by removing all transactions relating to money market loans from the settlement for a whole day. The loans are identified using the Furfine algorithm, which, based on an estimated money market interest rate r, matches payments on day t of value x with payments on day $t + 1$ of value $-(1 + r)x$ between two participants. Such payment flow probably represents the disbursement and repayment including interest of an overnight money market loan. The focus is solely on the overnight segment, which has constituted by far the largest share of the Danish money market since 2008.[10]

In the example in Table 1, the payments at 7:30 and 10:02 am are identified as money market transactions and removed. As a result, Bank C has insufficient liquidity for settlement of its payment at 12:15 pm. The direct effect of the MM scenario is

$$35/295 = 11.9 \text{ per cent,}$$

while the indirect effect is

$$20/260 = 7.7 \text{ per cent,}$$

and the multiplier effect is

$$20/35 = 57.1 \text{ per cent.}$$

In the example, the impact, in absolute figures and relative to the removed value, of removing the money market transactions is less negative for the system than removing Bank A's payments.

9 See Jørgensen et al. (2011).

10 Overnight loans include Overnight (O/N) and Tomorrow Next (T/N) loans. See Arciero et al. (2016) for a description of the Furfine algorithm and Abildgren et al. (2018) for its application to Kronos data.

Intraday Credit (IC) scenario:
the participants' access to intraday credit is reduced

Kronos' participants obtain access to intraday credit from Danmarks Nationalbank by collateralisation via pledging of eligible securities, including Danish government bonds and mortgage bonds.[11] Drops in the value of these securities will reduce the participants' credit lines, thereby limiting their ability to settle payments in a timely manner.

During the European sovereign debt crisis from 2009 onwards, the yield on government bonds issued by a number of countries, including Greece in particular, rose due to the governments' inability to meet their debt servicing obligations.[12]

In a worst-case scenario, a highly unlikely shock to the Danish economy resulting in surging increases in interest rates and falling government and mortgage bond prices could erode the participants' basis for intraday credit from Danmarks Nationalbank.

The third scenario (IC) mimics this situation by reducing the participants' available credit by 25 per cent, either due to a price fall on eligible securities or because the participant is forced to sell off securities in its custody account. In Table 1, the credit of all three participants is reduced by 25 per cent so that neither Bank C nor A has sufficient liquidity to settle their payments at 12:15 and 2:11 pm. The indirect effect of the IC scenario is

$$50/295 = 16.9 \text{ per cent.}$$

The direct effect is 0 per cent, as no payments are removed and therefore the multiplier effect cannot be calculated. In the example in Table 1, the IC scenario has a greater negative impact on the settlement of payments than the MM scenario, but this is exceeded by the dramatic impact of the RP scenario.

Assumptions and sources of error

The first critical assumption of all three scenarios is that the participants' actions are unchanged relative to the benchmark, regardless of the shocks to which the system is exposed: a participant will not respond to payments expected but not received, e.g. by changing the order of its payments or even cancelling them. On the contrary, the value and timing of any payment will remain constant. Nor can the participants help each other in a stress scenario by providing guarantees for a participant affected by failure and paying on its behalf. In other words, the scenarios are implemented by means of static simulations with deterministic payments without including the participants' dynamic behaviour.[13] In the RP scenario, however, this may be a reasonable assumption for a short period, as the participants are likely to remain passive for a while, until the problem is identified.

Another assumption is that the participants are unable to provide top-up collateral other than through traditional pledging as collateral the deposits in their custody accounts registered in the benchmark. In reality, the participants have access to regularly changing the deposits in their custody accounts by transferring other securities in their possession to the accounts, and they can also make payments under the automatic collateralisation arrangement[14] with VP. Depending on the background to a given liquidity shock to the system, the participants can probably increase their intraday credit lines in order to be better prepared for the liquidity shortfall.

A third key aspect of the analysis is that intervention by Danmarks Nationalbank is not an option. In the event of a real shock to Kronos, Danmarks Nationalbank can execute payments on behalf of the participants using the system's contingency procedures. Danmarks Nationalbank may also temporarily

11 For a complete list of eligible securities, see (*link*).

12 See e.g. Lane (2012).

13 This is a standard assumption in simulation studies based on historical data. Modelling of the participants' behaviour leads to further assumptions and increased complexity without this necessarily contributing significantly to the results of the analysis, cf. Lublóy and Tanai (2008) and ECB (2017). But simple agent-based modelling (ABM) may provide more insight into the resilience of the system. ABM will possibly be included in future stress tests of Kronos2.

14 The automatic collateralisation arrangement is not included in the analysis due to data shortage.

expand the collateral base by other security types in order to increase the participants' access to intraday credit against appropriate collateral.

The fourth assumption is that the ancillary systems are static: the amounts settled in Retail, VP and CLS accounts do not change. Consequently, the shocks inflicted on Kronos are not extended to include the ancillary systems. Obviously, this is an abstraction from reality, because e.g. dramatic price dives in the financial markets may very well change the net amounts submitted by the participants in the VP settlement system due to increased trade and payment of margin calls. Including the ancillary systems in an overall stress test is beyond the scope and data basis of this analysis.

A fifth limitation is that the scenarios span only one business day. The participants' balances and queued payments are not transferred to the following business day. So in the RP scenario, the stress test measures the impact of a participant's failure lasting one day, after which the problem is resolved and payments are settled after closing time before the beginning of the next business day. Extending the stress test to examining the impacts of scenarios over several business days would imply modelling the behaviour of the participants and Danmarks Nationalbank, as inaction over several days is highly unlikely. In this analysis, such an examination has been excluded from the stress test.

All else equal, the first three critical assumptions lead to overestimation of the negative impacts of the scenarios, while the last two lead to underestimation.

Results of the simulations

This section outlines selected results of the simulations. The RP, MM and IC baseline scenarios and combinations thereof are simulated for each business day from 2 January 2007 to 3 August 2018. Hence, the analysis covers a period of varying financial market conditions and levels of monetary policy interest rates. RP1-RP5 indicate that each of the five largest participants, ranked according to the value of payments submitted, are removed from the system. All in all, 52,092 daily simulations broken down by 2,894 business days, 17 scenarios and one benchmark were run.

Below, the presentation is narrowed to include the baseline scenarios and the worst case combination scenarios. For example, *RP1, MM & IC* indicate that the largest participant (Participant 1) and all money market loans are removed from the system, while the other participants' intraday credit is reduced by 25 per cent. The combination scenarios are hardly plausible, but they are included in the analysis to examine what could create considerable negative impacts.[15]

Two large participants and a money market of diminishing importance

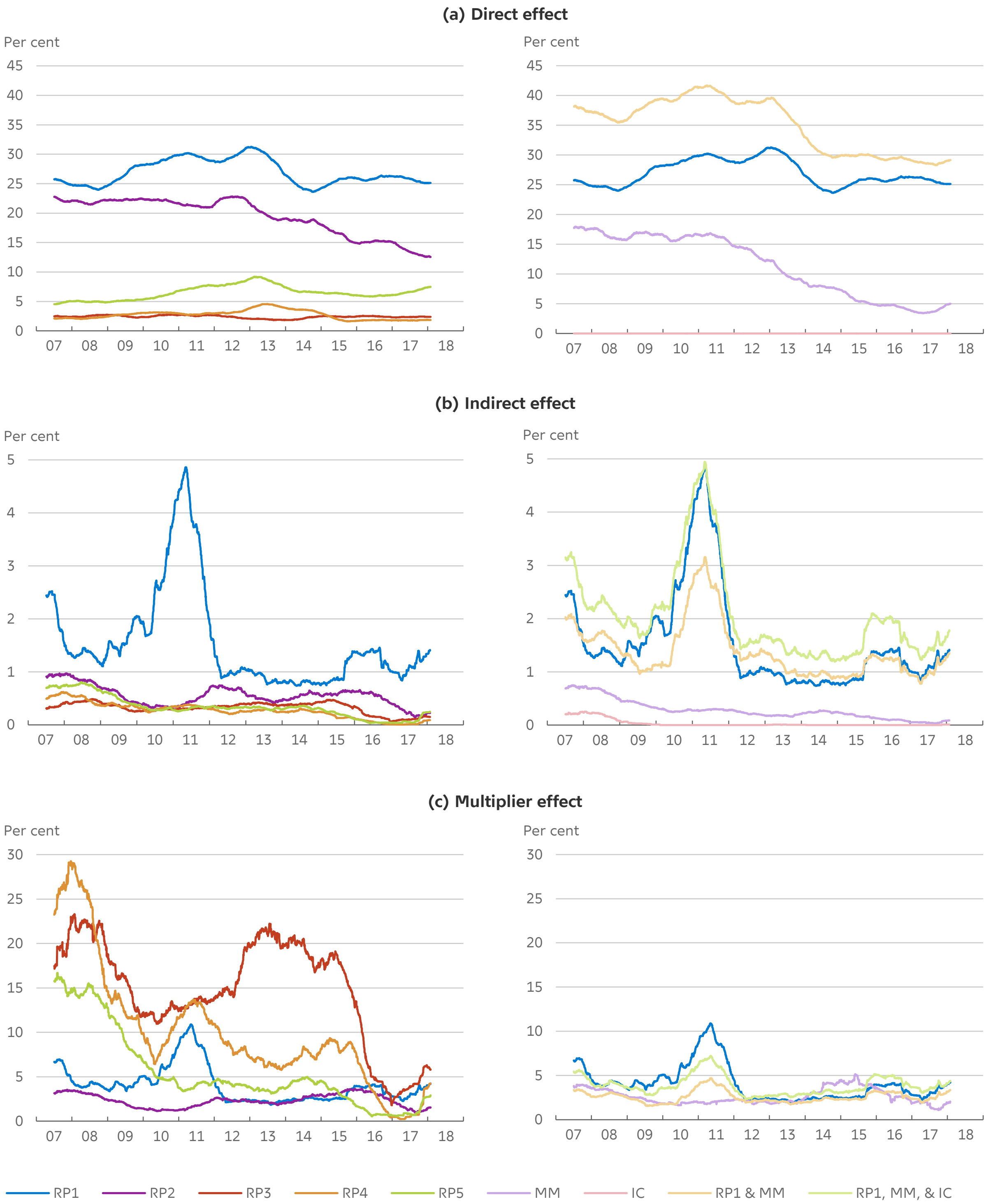
Chart 1(a) shows the direct effect of scenarios RP1-RP5, respectively, in the left-hand chart and RP1, MM, IC and the combination of RP1 & MM as well as RP1, MM & IC in the right-hand chart. The same divided presentation of the scenarios applies to the rest of the analysis charts below.

Chart 1(a) clearly shows that Participants 1 and 2 account for the predominant share of the value settled in the system. As a result, the first-order effect of these participants being unable to execute their payments is substantial. Participant 1's submitted payments consistently amounted to between 23 and 32 per cent of turnover during the period, while Participant 2's share fell from more than 20 per cent to around 13 percent. The direct effect of removing the three other large participants is around or below 5 per cent.

As can be seen, the unsecured money market loans accounted for close to 17 per cent of turnover in 2007-2011, but have fallen considerably since then and now account for less than 5 per cent. Not surprisingly, if the RP1 and MM scenarios are combined, the direct effect is even greater, approaching 42 per

15 The target has been an indirect effect of more than 5 per cent. This may also be referred to as a *reverse stress test*.

Effects of the scenarios Chart 1



Note: 12-month moving averages. The scenario codes are *RPX*: Remove Participant X; *MM*: Money Market; *IC*: Intraday Credit.
(a) The direct effect is the value of non-submitted payments in the scenario relative to submitted payments in the benchmark.
(b) The indirect effect is the value of unsettled payments relative to submitted payments in the scenario.
(c) The multiplier effect is the value of unsettled payments relative to non-submitted payments in the scenario.
Note that the curves for *RP1 & MM* and *RP1, MM, & IC* overlap in (a), as the direct effect of *IC* alone is 0 per cent. For the same reason, the multiplier effect cannot be calculated for *IC*, so the curve for *IC* alone is not shown in (c).
Source: Danmarks Nationalbank.

cent, while it is 0 per cent for the IC scenario, as no ransactions are removed.[16]

The derived effects of the scenarios are limited
The indirect effect reflects the multi-order effects of implementing the scenarios. Chart 1(b) shows that removal of Participant 1 undoubtedly has the greatest negative impact on the system compared to the other four scenarios. In 2007-2011, RP1 caused almost 5 per cent of the other payments submitted to remain unsettled at the end of the day. By comparison, the effects of RP2-RP5 are consistently below 1 per cent.

The indirect effect of the MM scenario decreases in step with the reduced importance of the money market from just under 1 per cent to close to 0 per cent over the period. The impact of the IC scenario is negligible, meaning that the participants' liquidity management depends only to a low degree on their access to intraday credit via traditional collateralisation. But the IC scenario has an amplifying effect when combined with both RP1 and MM, which gives the highest indirect effect.

The indirect effect does not exceed 5 per cent, however, meaning that even in the worst case scenario, more than 95 per cent of the remaining payments are still settled. Somewhat surprisingly, the combination of RP1 and MM has a lower indirect effect than RP1 alone. This is because a number of the unsettled payments in RP1 are money market loans that are removed in the combination scenario. It should be emphasised that this is an average effect. The variation from day to day is discussed below.

A common feature of the RP scenarios is a substantial increase in the indirect effect in 2010. This correlates with the participants voluntarily stopping to raise monetary policy loans from Danmarks Nationalbank. The reason may be that the participants' credit requirements are reduced or that the participants have chosen not to raise loans for fear of the signal value of being dependent on Danmarks Nationalbank's facilities.[17] The latter may have put the participants' liquidity management under pressure, resulting in a higher indirect effect when the system is exposed to liquidity shocks in the stress scenarios.

The indirect effect then dives in 2012. The main reason is an increase in the participants' current account balances, which coincides with the transition to negative interest rates on certificates of deposit and in the money market. Since the current account rate has been kept at 0 per cent, the participants have had an incentive to hold liquidity in current accounts rather than in the market at closing time, so large amounts of liquidity have been immediately accessible for payments at the beginning of the next business day. Normalisation of monetary policy conditions, i.e. a positive spread between money market interest rates and the current account rate, appears to indicate an increased risk of unsettled payments in a stress situation.

Multiplier impacts
The direct effect of removing Participants 3 and 4 is low, but then the multiplier effect, i.e. the indirect effect relative to the value removed, is high, cf. Chart 1(c). For each krone paid by Participant 3 that is removed, between kr. 0.10 and 0.25 of the other payments is not settled between 2007 and 2015.

In the RP3 scenario, however, the main reason is a single small participant[18] working with very low available liquidity. This participant finances practically all its submitted payments late in the day with payments received early in the day. The participant is removed from the settlement in the course of 2016. The multiplier impacts of the other RP scenarios and the combination scenarios are not very pronounced.

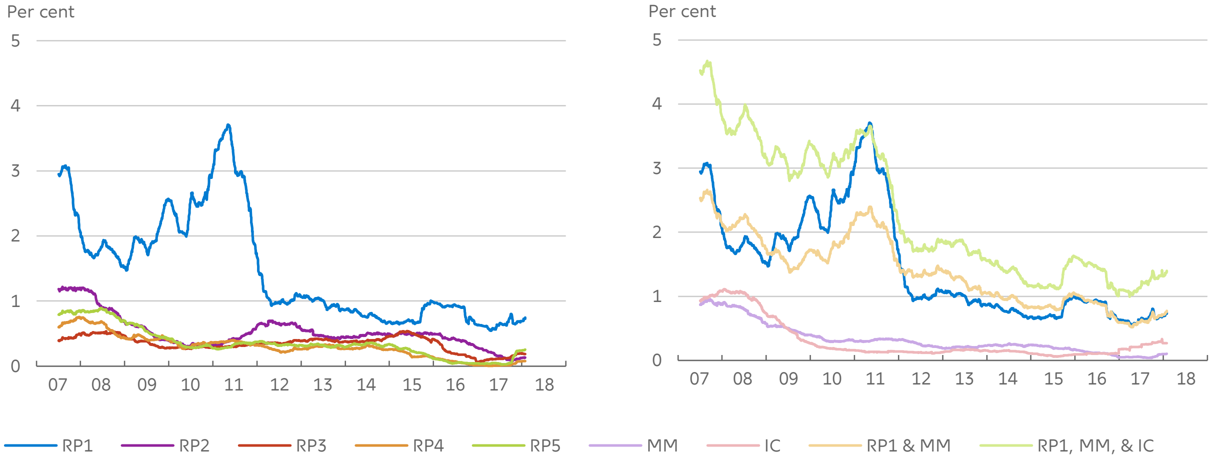
Delay of payments during the day
The indirect effect reflects only the number of payments delayed until the end of the day. It does not include the payments placed in a liquidity queue over the day, but being settled before closing time.

16 Note that the direct effect of *RP1* and *MM*, respectively, does not add up to the direct effect of *RP1 & MM*, because a subset of Participant 1's payments concern money market loans.

17 Stigma associated with money market facilities is well known in relation to the Federal Reserve's *Discount Window*, see Armantier et al. (2015).

18 I.e. a small bank different from Participant 3.

Delay indicator for the scenarios Chart 2



Note: 12-month moving averages. The scenario codes are *RPX*: Remove Participant X; *MM*: Money Market; *IC*: Intraday Credit. The delay indicator is a time and value-weighted average of the queued payments, cf. Technical appendix.
Source: Danmarks Nationalbank.

Due to the time-critical nature of the Kronos payments, a delay over the day may be as detrimental to financial stability as any unsettled payments at the end of the day.

The delay indicator is a time and value-weighted measure of delay in the system that includes all queued payments. Details on the indicator are available in Technical appendix. Chart 2 shows that developments in the delay indicator largely mirror developments in the indirect effect. The ranking of the respective scenarios is also the same, i.e. *RP1, MM & IC* is worst, followed by *RP1*, *RP1 & MM* and so forth.

The level of the delay indicator is substantially higher in 2007-2012, however. In this period, considerable liquidity queues form over the day with potentially major negative consequences for the counterparties affected. This is particularly true of the combination scenario *RP1, MM & IC*. The delay indicator thus illustrates a clearer impact of the transition to the new levels of monetary policy interest rates in 2012.

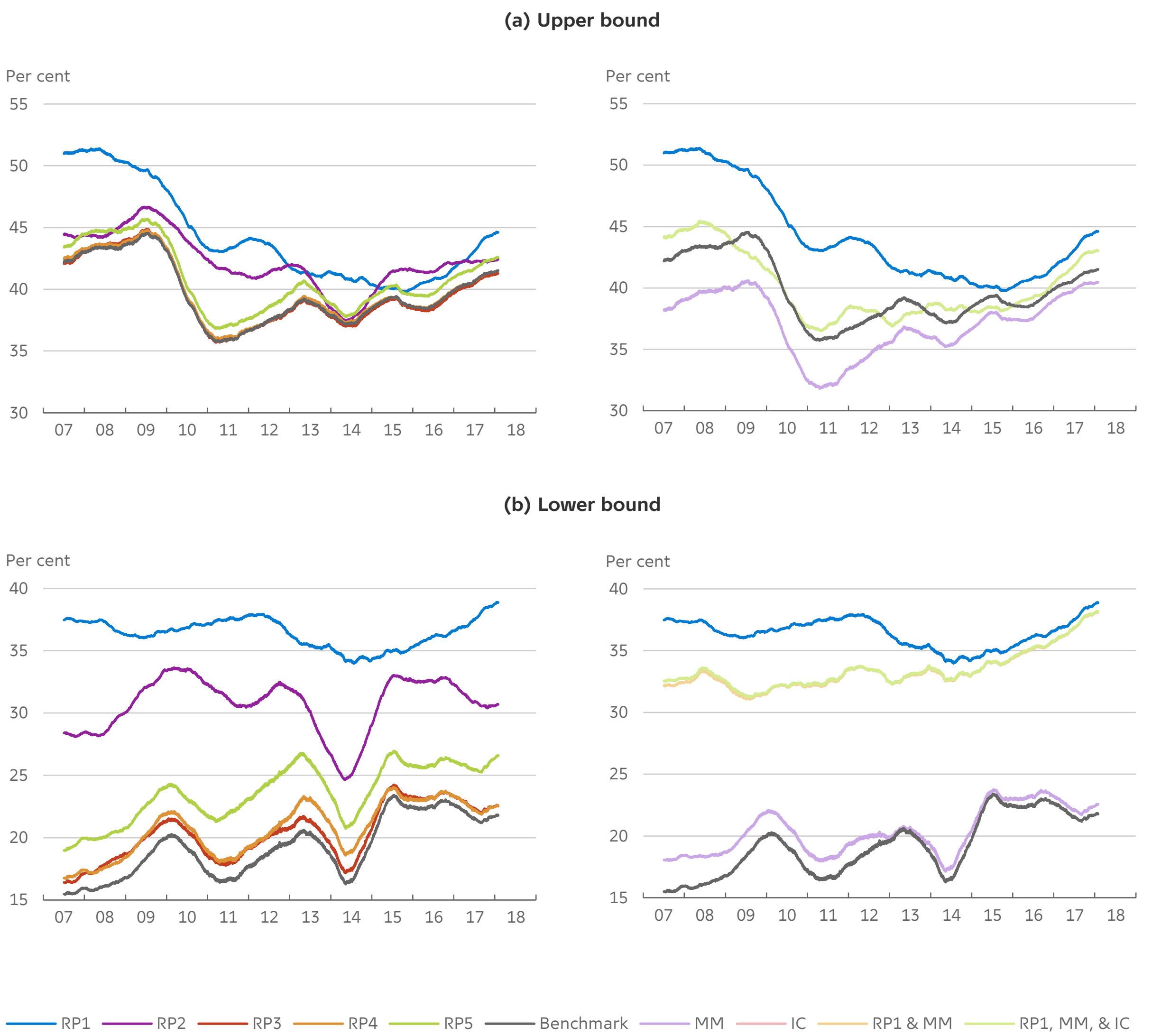
The scenarios result in few unsettled payments, but major changes in liquidity requirements

The actual liquidity requirement of a participant is between an upper and lower bound. Calculations and details appear from Technical appendix. A liquidity requirement of 0 per cent means that the participant is able to finance all its payments submitted solely by payments received.

On the other hand, a liquidity requirement of 100 per cent indicates that the participant has to finance all its payments submitted using its available liquidity, i.e. current account deposits and available credit. The upper bound takes into account the order of the payments, while this is not the case with the lower bound. Assume, for example, that a payment at 10 am is delayed until noon. A participant expects to receive liquidity at 10 am, and that liquidity is to be used to submit another payment at 11 am. As the payment received is delayed, the upper bound of the participant's liquidity requirement increases. However, as the payment received is settled before the end of the day the participant's lower bound remains unchanged.

Chart 3 shows the development in (a) the upper and (b) the lower bound, respectively, of the participants' liquidity requirements. The chart is read by comparing each curve for the scenarios to the curve for the benchmark. The RP1 scenario leads to an increase in the upper bound of up to 9 percentage points and in the lower bound of up to 22 percentage points in 2007. The impact of the RP2 scenario is less pronounced, but still substantial.

Impact of the scenarios on liquidity requirements Chart 3



Note: 12-month moving averages. The scenario codes are *RPX*: Remove Participant X; *MM*: Money Market; *IC*: Intraday Credit. The participants' liquidity requirements are between the upper and lower bound of each scenario, cf. Technical appendix.
Source: Danmarks Nationalbank.

Removing the two largest participants thus results in severe liquidity shocks to the other participants in the system.

The development in the liquidity requirement bounds across the RP scenarios is consistent with the delay indicator in Chart 2: RP1 has the most significant effect, especially in 2007 and 2011, and the significance of RP2 is decreasing, while RP3-RP5 are only just above the benchmark. Across the combination scenarios in the right-hand chart, only RP1 alone leads to the most substantial change in the upper bound. The reason is that the order of the money market transactions actually increases the liquidity requirement relative to the benchmark. This reduces the upper bound in the MM scenario as well as in both combination scenarios. On the other hand, the lower bound clearly shows that the participants have higher liquidity requirements in the scenarios than in the benchmark.

Increases in the liquidity requirements of up to 22 percentage points do not lead to more unsettled payments than a few per cent on average. This emphasises the surplus liquidity available in the system during the period analysed.

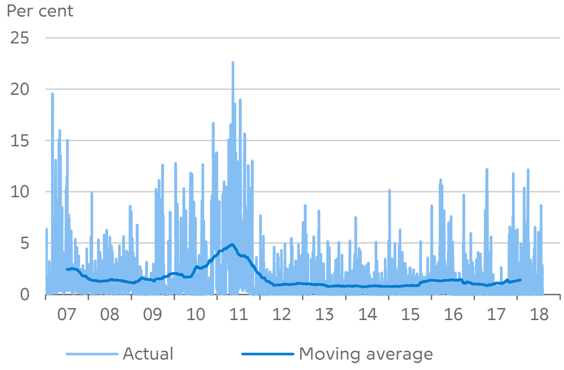
Variation in the indirect effect from day to day
The 12-month moving averages may mask substantial variations in the negative impacts between the days, however. Chart 4 shows two curves for the indirect effect of RP1: the actual daily value and the moving average over the year. Although the effect is close to 0 per cent on most days, up to 22 per cent of the payments cannot be settled if the largest participant is removed from the system on individual *critical days*.

As expected, half of the critical days are on fixed dates with high activity in Kronos, including days when wages are paid, tax payments are made, short-term mortgage bonds are refinanced, etc. The days before and after both Danish and international public holidays are also expected to be critical. The other half of the critical days are on dates that are not immediately predictable based on recurring events.

On the critical days, the indirect effect measured by *value* is substantial, while it is limited when measured by *number*. For example, on the worst day in 2017, all but 29 payments are settled. The total value of these payments is kr. 20.7 billion, resulting in an indirect effect of 12.2 per cent. In terms of value, most of these transfers are to ancillary systems, including the VP settlement system and the Intradagclearing in particular. These transfers are typically standing orders[19] comprising considerable excess cover in relation to the net amounts the participants have to submit for settlement purposes. The other major unsettled payments are for precisely that participant which is removed from the settlement, so they reflect a liquidity sink effect. The transaction amounts of both of these transaction types can probably be adjusted by the participants in an actual stress situation.

Furthermore, the 29 unsettled payments are attributable to very few non-submitted payments of high

Fluctuations in the indirect effect of RP1 Chart 4



Note: The indirect effect is the value of unsettled payments relative to payments submitted in the Remove Participant 1 scenario.
Source: Danmarks Nationalbank.

value from Participant 1. As a consequence, the extent of the failure leading to delays in the system in the worst scenario on the worst day in 2017 is limited to a handful of participants and their relatively few large payments to their own settlement accounts or to each other.

Discussion and future analysis

The stress test provides an indication of the participants' liquidity situation and the resilience of the system in a deterministic world with static behaviour. In this way, potential problems are identified that can actually be wholly or partly resolved by the dynamic behaviour of the participants and Danmarks Nationalbank.[20] The stress test analysis will be able to identify vulnerabilities which can profitably be addressed in advance.

The conclusion of this analysis is that no changes are required. The system is exposed to severe

19 Pre-entered transactions submitted at fixed times.

20 The participants' dynamic behaviour may also create problems for the system if they act inappropriately. That situation is excluded here, however.

shocks to the participants' liquidity, and even though this substantially increases their liquidity requirements, it leads, on average, to very modest delays and few unsettled payments. On a few critical days, the negative impacts of the scenarios can be several times higher than the average, but as this is caused by a few very large payments, the impacts can be reduced by executing those payments manually using Kronos' contingency procedure. However, this means that the participants must regularly identify their own critical payments, those submitted as well as those received, and test their internal processes when making payments using Kronos' contingency procedure.

The ongoing stress test efforts continue with the focus on including data from Kronos2 and on refining the scenarios.

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Technical appendix

This appendix reviews calculations and interpretations of the upper and lower bounds of the liquidity requirement and the delay indicator.

The appendix applies the following standard notation: $x_d^{ij}(t)$ indicates a payment of kr. x from participant i to participant j on day d and at time t, where

- $x \in \mathbb{R}^+$ is the value of the payment
- $i, j \in \{1,2,\ldots,N\}$ are two participants among N active participants in the system
- $d \in \{1,2,\ldots,D\}$ is a business day between Tuesday, 1 January 2007 $(d = 1)$ and Friday, 3 August 2018 $(d = D)$, i.e. the first and last business day of the period analysed
- $t \in [0, T]$ is the time from Kronos opens at 7:00 am $(t = 0)$ until it closes at 3:30 pm $(t = T)$.

Liquidity requirement bounds

Participant i's net debit position on day d and at time t is

$$\delta_d^i(t) = \sum_{k=0}^{t} \sum_{j \neq i} x_d^{ij}(k) - x_d^{ji}(k).$$

The *upper bound* U_d^i for participant i's liquidity requirement on day d is the maximum of the participant's net debit position over the day, i.e.

$$U_d^i = \max_{t \in [0,T]} \max\{\delta_d^i(t), 0\}.$$

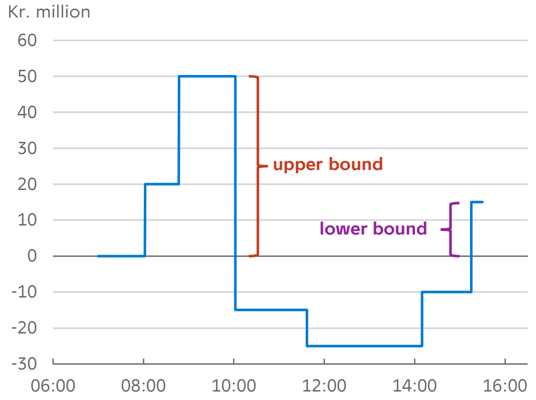
U_d^i indicates the level of liquidity which participant i must have at its disposal when $t = 0$ on day d, in order for all participant i's submitted payments to be settled in their actual order during the day.

The *lower bound* L_d^i for participant i's liquidity requirement on day d is the participant's net debit position at the end of the day, i.e.

$$L_d^i = \max\{\delta_d^i(T), 0\}.$$

Similarly, L_d^i is the level of liquidity which participant i must submit if all participant i's payments are netted multilaterally against all the other participants' $(j \neq i)$ payments for all of day d.

Example of cash flow and liquidity requirement bounds Chart 5



Note: The curve shows a participant's net debit position, which increases (decreases) when payments are submitted (received).
Source: Own work.

In other words, L_d^i is the value of participant i's submitted payments less the value of participant i's received payments over day d.

Chart 5 above shows an example of a participant's net debit position over a day. A *positive* value at a given time means that the participant would have a corresponding *negative* current account balance if the participant had started the day with a balance of zero. In the example, the participant must have available liquidity of kr. 50 million to be able to settle its payments in their actual order (the upper bound), but is only required to have available liquidity of kr. 15 million if all payments are netted and settled at the end of the day (the lower bound).

In a stress scenario, both bounds of the participants' liquidity requirements can increase, as some payments are removed and other payments are thus delayed or not effected. Hence, a given participant must typically have a larger amount of liquidity at its disposal in order to execute its payments in a timely manner. The upper bound implicitly assumes that the participant will not change the order of its submitted payments, even though certain payments expected to be received are not effected. The lower bound is a more abstract entity, because when payments are not automatically netted, multilateral netting must assume that the participants are fully aware of each other's cash flows and capable of perfectly coordinating payments which cancel out their respective obligations. The actual liquidity requirement in a stress situation is between the two bounds, but undoubtedly closer to the upper bound.

U_d^i is calculated at participant level per day and aggregated to system level per day by adding up the participants

$$U_d = \sum_{i=1}^{N} U_d^i.$$

In order to achieve a relative measure, the aggregate is viewed in relation to all payments submitted in the system

$$P_d = \sum_{i=1}^{N} \sum_{j \neq i} \sum_{t \in [0,T]} x_d^{ij}(t),$$

and thus the upper bound relative to the payments in the system is

$$u_d = \frac{U_d}{P_d}.$$

Finally, a 12-month moving average centred on a given day d_0 is calculated as

$$u_{d_0}^{\text{avg}} = \frac{1}{250} \sum_{d \in Y_0} u_d,$$

$$Y_0 = \{d_0 - 125, \dots, d_0, \dots, d_0 + 124\},$$

as a year averages 250 Danish business days. The same procedure applies to the other indicators, so an average of relative aggregates is shown in Chart 1, Chart 2 and Chart 3.

The delay indicator
Below, $x_d^{ij}(t,\tau)$ indicates a payment submitted at time t, but not settled until time τ. For $t < \tau < T$, the payment is delayed and for $\tau = T$, the payment is unsettled.

The delay indicator per day is given by

$$\xi_d = \frac{\sum_{i=1}^{N} \sum_{j \neq i} \sum_{\tau \neq t} (\tau - t) x_s^{ij}(t,\tau)}{\sum_{i=1}^{N} \sum_{j \neq i} \sum_{\tau \neq t} (T - t) x_s^{ij}(t,\tau)},$$

i.e. the time and value-weighted share of queued payments on day d. This means that a payment of kr. 1 delayed by 2 hours has the same weight as a payment of kr. 2 delayed by 1 hour. When $\xi_d = 0$, all payments have been settled in a timely manner, and in the extreme event of $\xi_d = 1$, all payments have been delayed until closing time, meaning that they are unsettled.

The indicator sheds light on liquidity queues forming over the day, but being settled before the end of the day. However, such liquidity queues may have a similar or even greater negative impact on the settlement of payments than the few, if any, unsettled payments remaining at closing time as the Kronos payments are time critical.

ABOUT ANALYSIS

As a consequence of Danmarks Nationalbank's role in society we conduct analyses of economic and financial conditions.

Analyses are published continuously and include e.g. assessments of the current cyclical position and the financial stability.

The analysis consists of a Danish and an English version. In case of doubt regarding the correctness of the translation the Danish version is considered to be binding.

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FINANCIAL STABILITY

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