# Appendix A
# Liquidity Model

## A.1 Cash Flow Expectations

### Conditional versus Unconditional Expectations

Unconditional expectations are expectations for a future time point $t_{k+1}$ taken at $t_0$. Unconditional cash flow expectation writes as:

$$
\begin{aligned}
E[CF_{t_{k+1}}|F_{t_0}] &= E[CF_{t_{k+1}}] \\
F_{t_0} &= \{\Omega, \oslash\}
\end{aligned}
$$

At $t_0$, the minimal information is available: 'something will happen'. This is formalized by the information set $F_{t_0} = \{\Omega, \oslash\}$.

Conditional expectations are expectations for the same future time point $t_{k+1}$, but taken at $t_k$. Conditional expectations are denoted:

$$E[CF_{t_{k+1}}|F_{t_k}]$$

Conditional expectations use the information set $F_{t_k}$ instead of $F_{t_0}$. $F_{t_k}$ contains all information that have been revealed between $t_0$ and $t_k$. Applied to our context, $F_{t_k}$ contains all past cash flows. Seen from $t_0$, the conditional expectation is a random variable as it is not known which information will be revealed.

Conditional and unconditional expectations are identical if the process is independent on the revealed information. This means that the process is path-independent. Applied to our context this implies that past cash flows do not provide any information about future cash flows.

The following section discusses the implications of the expectation type for unrestricted and restricted products. We base our arguments on a product without jumps. However, the arguments also hold for products with jumps.

**Unrestricted Products**

In a first step, we discuss conditional and unconditional expectations for ideal (unrestricted) products. An unrestricted product can take balances between $(-\infty,+\infty)$ and does never expire.

With respect to inventories $X_{t_{k+1}}$ , the conditional expectation $E[X_{t_{k+1}}|F_{t_k}]$ differs almost sure from unconditional expecation $E[X_{t_{k+1}}|F_{t_0}]$ as (A.1) suggests:

$$\begin{aligned} E[X_{t_{k+1}}|F_{t_0}] &= E[X_{t_k}] + \mu_{t_{k+1}}\Delta t \\ &\overset{a.s.}{\neq} X_{t_k} + \mu_{t_{k+1}}\Delta t \\ &= E[X_{t_{k+1}}|F_{t_k}] \end{aligned} \tag{A.1}$$

With respect to $t_0$, the inventory $X_{t_k}$ is unknown. Thus, it has to be estimated by $E[X_{t_k}]$. With respect to $t_k$, the particular realization of $X_{t_k}$ is known. As $X_{t_k}$ differs almost sure from its expectation, conditional and unconditional expectations are different.

The fact that unconditional expectation requires an additional estimation of $X_{t_k}$ is reflected by a higher variance:

$$\begin{aligned} Var[X_{t_{k+1}}|F_{t_0}] &= Var[X_{t_k} + \mu_{t_{k+1}}\Delta t + \sigma\Delta W_{t_{k+1}}|F_{t_0}] \\ &= Var(X_{t_k}|F_{t_0}) + \sigma^2\cdot\Delta t \\ &> \sigma^2\cdot\Delta t \\ &= Var[X_{t_{k+1}}|F_{t_k}] \end{aligned}$$

The variance of the $t_{k+1}$-inventory is higher seen from $t_0$ than seen from $t_k$. The intuition is that it is easier to forecast the level of the next time point knowing where the process currently is than to forecast the level from the starting point.

Obviously, taking into account information between $t_0$ and $t_k$ reduces uncertainty about the inventory in $t_{k+1}$.

This is not true with respect to cash flows:

$$\begin{aligned} E[CF_{t_{k+1}}|F_{t_k}] &= (\mu^i_{t_{k+1}}\cdot\Delta t + \sigma^i_{t_{k+1}}\Delta W^i_{t_{k+1}}) \\ &= (\mu^i_{t_{k+1}})\cdot\Delta t \\ E[CF_{t_{k+1}}|F_0] &= (\mu^i_{t_{k+1}}\cdot\Delta t + \sigma^i_{t_{k+1}}\Delta W^i_{t_{k+1}}) \\ &= (\mu^i_{t_{k+1}})\cdot\Delta t \\ &= E[CF_{t_{k+1}}|F_{t_k}] \end{aligned}$$

The level is not relevant for the cash flow forecast: the cash flow for $t_{k+1}$ as expected at $t_0$ is exactly the same as expected at $t_{k+1}$. Hence, knowing past cash flows does not improve the cash flow forecast for $t_{k+1}$. This is confirmed by the variance:

$$\begin{aligned}
Var[CF_{t_{k+1}}|F_{t_k}] &= Var[\mu^i_{t_{k+1}} \cdot \Delta t + \sigma^i_{t_{k+1}} \Delta W^i_{t_{k+1}} | F_{t_k}] \\
&= (\sigma^i_{t_{k+1}})^2 \Delta t \\
Var[CF_{t_{k+1}}|F_0] &= Var(\mu^i_{t_{k+1}} \cdot \Delta t + \sigma^i_{t_{k+1}} \Delta W^i_{t_{k+1}}) \\
&= (\sigma^i_{t_{k+1}})^2 \cdot \Delta t \\
&= Var[CF_{t_{k+1}}|F_{t_k}]
\end{aligned}$$

Uncertainty with respect to $CF_{t_k+1}$ is not reduced knowing past cash flows. Knowing past cash flows does not provide any information about future cash flows. This property is termed path-independence.

We conclude that knowing past cash flows reduces the uncertainty about future inventories, but not about future cash flows. Using conditional expectations improves the forecast of inventories, but not that of cash flows.

### Restricted Products

Real products are usually restricted in amount and/ or time (maturity). In the following, we analyze the implications for the statistical properties of cash flows. To illustrate our ideas, we take the example of a loan commitment with a lower bound of 0 and an upper bound of Z. Inventory and cash flow of the loan commitment restricted to [0,Z] are described by:

$$\begin{aligned}
\overline{\underline{X}}_{t_{k+1}} &= \min(\max(\overline{\underline{X}}_{t_k} + CF_{t_{k+1}}, 0), Z) \\
&= \overline{\underline{X}}_{t_k} + \min(\max(CF_{t_{k+1}}, -\overline{\underline{X}}_{t_k}), Z - \overline{\underline{X}}_{t_k}) \\
&= \overline{\underline{X}}_{t_k} + \overline{\underline{CF}}_{t_{k+1}}
\end{aligned}$$

Being:

$\overline{\underline{CF}}_{t_{k+1}}$ :Restricted Cash Flow

$$\begin{aligned}
\overline{\underline{CF}}_{t_{k+1}} &= \min(\max(CF_{t_{k+1}}, -\overline{\underline{X}}_{t_k}), Z - \overline{\underline{X}}_{t_k}) \\
&= \min(\max(CF_{t_{k+1}}, -\sum_{j=0}^{k} \overline{\underline{CF}}_{t_j}), Z - \sum_{j=0}^{k} \overline{\underline{CF}}_{t_j})
\end{aligned} \tag{A.2}$$

Hence, the restricted cash flow is the original cash flow restricted to $[-\overline{\underline{X}}_{t_k}, Z - \overline{\underline{X}}_{t_k}]$. Product restrictions translate into cash flow restrictions. (A.2) suggests that future cash flows depend on past cash flows. Product restrictions make cash flows path-dependent. This is in contrast to unrestricted products.

Now, it makes a difference for the cash flow forecast whether the current level is known ($t_k$-information) or has to be estimated ($t_0$-information). Obviously, using the information revelead between $t_0$ and $t_k$ reduces the uncertainty about future cash flows:[1]

$$Var(\overline{\underline{CF}}_{t_{k+1}}|F_{t_k}) \leq Var(\overline{\underline{CF}}_{t_{k+1}}) \tag{A.3}$$

[1] The conditional variance defines [Shiryaev, 1996, p.214].

In contrast to unrestricted products, cash flow forecasts of restricted products should use conditional expectations and not unconditional expectations. The level-depending restrictions make past information $F_{t_k}$ valuable to forecast cash flows. Consider the following example: knowing that the loan commitment is completely drawn in $t_k$, ($X_{t_k} = Z$) implies that the probability of additional cash outflows $CF_{t_{k+1}}$ is zero.

The more restricted a product, the more additional information reduces cash flow uncertainty all other things being equal. Consider the following example: loan commitments that are restricted to [0,$X_{t_k}$] are more restrictive than loan commitments that are restricted to [0,Z]. The restriction $[0, X_{t_k}]$ means that the next balance has to be either lower than the current balance or equal. In other words: the commitment has to be repaid and cannot be drawn again. This property is called 'non-revolving' and ensures a monotonicity in the inventory evolution. Obviously, 'non-revolving' is more restrictive than a constant upper boundary Z.

Setting $Z = X_{t_k}$, (A.2) becomes:

$$\overline{\underline{CF}}_{t_{k+1}} = \min(\max(CF_{t_{k+1}}, -\overline{\underline{X}}_{t_k}), 0)$$

To illustrate how the knowledge of the current level can reduce uncertainty, let us assume that the loan commitment has been repaid, i.e. $\overline{\underline{X}}_{t_k} = 0$. For that particular case, we get:

$$\begin{aligned}\overline{\underline{CF}}_{t_{k+1}} &= \min(\max(CF_{t_{k+1}}, 0), 0)\\ &= 0\end{aligned}$$

Knowing that the non-revolving loan commitment has been repaid eliminates any uncertainty: $CF_{t_{k+1}}$ must be zero. From a $t_0$-perspective, the level is always uncertain. Consequently, a $t_0$-forecast can never discard cash flow uncertainty.[2]

We conclude that product restrictions make future cash flows depending on past cash flows. Knowing past cash flows reduces cash flow uncertainty. For non-revolving products, knowing the past might even lead to complete certainty. As a result, the use of conditional expected cash flows is preferable to the use of unconditional expected cash flows. The more products are restricted, the more valuable is the use of conditional expectations.

### Suboptimality and Attenuation

Clearly, using unconditional expectations for real (restricted) products is suboptimal.

This section discusses how the suboptimality can be reduced.

As table A.1 suggests products have different degrees of restrictions: $X_{t_k}$ denotes the product volume at $t_k$. Products 2-5 describe restricted products. Product 1 is an (ideal) unrestricted product. The products 2-4 are restricted in amount, product 5 is restricted in time (fixed maturity). Products can be restricted with respect to amount- and/ or time.

The importance of conditional expectations is decreasing in the degree of restrictions.

There are three ways to attenuate the suboptimality of using unconditional instead of conditional expectations:

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[2] An exception is the rather 'pathological' case that the loan committment is already repaid in $t_0$.

**Table A.1** Degrees of Product Restrictions

| Number | Example | Amount | Maturity |
|---|---|---|---|
| 1 | Current Account incl. ∞-Overdraft | — | — |
| 2 | Saving Deposits | $0 \leq X_{t_k}$ | — |
| 3 | Loan Committments | $0 \leq X_{t_{k+1}} \leq Z$ | — |
| 4 | Amortizing Loans | $0 \leq X_{t_{k+1}} \leq X_{t_k}$ | — |
| 5 | Like (1), fixed maturity | — | $t_m$ |

1. Limiting Model Horizon
   Clearly, the divergence between conditional and unconditional expectations increase in time as every time step reveals information which conditional expectations incorporate and unconditional expectations ignore. Limiting the model horizon limits the suboptimality.
2. Make 'Non-revolving' products revolving
   Non-revolving products can be made 'revolving' by modelling existing and future new business (incl. prolongations) as one product. Deviations of the new business net with deviations of the existing business. As a result, the expectation stabilizes and unconditional expectations exhibit a smaller model error.
3. Customer Modelling instead of product modelling
   Products are an artificial segmentation of customer needs: a customer that holds a savings and a current account can continue to withdraw on the current account if the savings account is on zero. Seen as one unit, the product 'savings and current account' is unrestricted. Hence, it might be preferable to use the customer as modelling unit instead of products. However, customer modelling can only be done for customers that hold almost all products with the same bank. Customers holding current accounts with several banks cannot be modelled on a customer basis.

# Appendix B
# Liquidity Management

## B.1 Brownian Transfer Prices for Large and Homogeneous Portfolios

Given (5.11), $\gamma$ and $\gamma^p$ simplify to:

$$\begin{aligned}
\gamma &= \frac{\sigma^A}{\sigma^P + \sigma^M} \\
&= \frac{\sqrt{\sum_{i=1}^d (\sigma^p)^2 + (\sum_{i=1}^d \sigma^m)^2}}{\sqrt{\sum_{i=1}^d (\sigma^p)^2} + \sum_{i=1}^d \sigma^m} \\
&= \frac{\sqrt{d \cdot (\sigma^p)^2 + (d \cdot \sigma^m)^2}}{\sqrt{d \cdot (\sigma^p)^2} + d \cdot \sigma^m} \\
&= \frac{d}{d} \cdot \frac{\sqrt{\frac{(\sigma^p)^2}{\sqrt{d}} + (\sigma^m)^2}}{\frac{\sigma^p}{\sqrt{d}} + \sigma^m} \\
&= \frac{\sqrt{\frac{(\sigma^p)^2}{\sqrt{d}} + (\sigma^m)^2}}{\frac{\sigma^p}{\sqrt{d}} + \sigma^m} \\
\gamma^p &= \frac{\sigma^P}{\sum_{i=1}^d \sigma^p} \\
&= \frac{\sqrt{\sum_{i=1}^d (\sigma^p)^2}}{\sum_{i=1}^d \sigma^p} \\
&= \frac{\sqrt{d} \cdot \sigma^p}{d \cdot \sigma^p} \\
&= \frac{1}{\sqrt{d}}
\end{aligned}$$

Having a large product spectrum ($d \to \infty$) yields:

$$\lim_{d\to\infty}\gamma = \frac{\sqrt{\frac{(\sigma^p)^2}{\sqrt{d}} + (\sigma^m)^2}}{\frac{\sigma^p}{\sqrt{d}} + \sigma^m}$$
$$= 1$$
$$\lim_{d\to\infty}\gamma^p = \frac{1}{\sqrt{d}}$$
$$= 0$$

# Appendix C
# Liquidity Optimization

## C.1 Optimization in Origination Department

We use the following differentiation rule[1]:

$$\frac{d}{dx}\int_a^x f(t)dt = f(x)$$

and:

$$\frac{d}{dx}\int_a^{g(x)} f(t)dt = f(x)\cdot g'(x) \tag{C.1}$$

Based on this initial relation, we derive two lemmata.

**Lemma C.1.** *It holds:*

$$\frac{\partial E[\max(x(\alpha)-\beta,0)]}{\partial\alpha} = \frac{\partial x}{\partial\alpha}\cdot P(\beta \leq x(\alpha))$$

Derivation of lemma C.1:

[1] See [I.N.Bronstein et al., 2000, p.468].

$$
\begin{aligned}
E[\max(x(\alpha)-\beta,0)] &= \int\limits_0^{x(\alpha)} (x(\alpha)-\beta)f(\beta)d\beta \\
&= x(\alpha)\int\limits_0^{x(\alpha)} f(\beta)d\beta - \int\limits_0^{x(\alpha)} \beta f(\beta)d\beta \\
\frac{\partial E[\max(x(\alpha)-\beta,0)]}{\partial\alpha} &= \frac{\partial\left(x(\alpha)\int_0^{x(\alpha)} f(\beta)d\beta - \int_0^{x(\alpha)} \beta f(\beta)d\beta\right)}{\partial\alpha} \\
&= [1\cdot\frac{\partial x}{\partial\alpha}]\cdot[\int\limits_0^{x(\alpha)} f(\beta)d\beta] \\
&+ [x]\cdot[f(x)\frac{\partial x}{\partial\alpha}] \\
&- x(\alpha)f(x(\alpha))\frac{\partial x}{\partial\alpha} \\
&= \frac{\partial x}{\partial\alpha}\cdot[\int\limits_0^{x(\alpha)} f(\beta)d\beta] \\
&= \frac{\partial x}{\partial\alpha}\cdot P(\beta\le x(\alpha)) \\
\frac{\partial E[\max(x(\alpha)-\beta,0)]}{\partial\alpha} &= \frac{\partial x}{\partial\alpha}\cdot P(\beta\le x(\alpha))
\end{aligned}
$$

**Lemma C.2.** *It holds:*

$$\frac{\partial E[\max(x(\alpha)-\beta)^2]}{\partial\alpha} = 2\cdot\frac{\partial x}{\partial\alpha}\cdot(x(\alpha)-E[\beta|\beta\leq x(\alpha)])\cdot P(\beta\leq x(\alpha)) \tag{C.2}$$

Derivation of lemma (C.2):
Note the following:

$$\begin{aligned}
E(\max(x(\alpha)-\beta,0)^2 &= \int\limits_0^{x(\alpha)}(x(\alpha)-\beta)^2 f(\beta)d\beta \\
&= \int\limits_0^{x(\alpha)}(x(\alpha)^2-2x(\alpha)\beta+\beta^2)f(\beta)d\beta \\
&= \int\limits_0^{x(\alpha)}(x(\alpha)^2-2x(\alpha)\beta+\beta^2)f(\beta)d\beta \\
&= x(\alpha)^2\int\limits_0^{x(\alpha)} f(\beta)d\beta \\
&- 2x(\alpha)\int\limits_0^{x(\alpha)}\beta f(\beta)d\beta \\
&+ \int\limits_0^{x(\alpha)}\beta^2 f(\beta)d\beta
\end{aligned} \tag{C.3}$$

The derivation of (C.3) w.r.t. $\alpha$ yields:

$$\begin{aligned}
\frac{\partial E[TV]}{\partial \alpha} &= [2x(\alpha)\cdot\frac{\partial x}{\partial \alpha}]\cdot[\int_0^{x(\alpha)} f(\beta)d\beta] \\
&+ [x(\alpha)^2]\cdot[f(x(\alpha))\frac{\partial x}{\partial \alpha}] \\
&- 2([1\cdot\frac{\partial x}{\partial \alpha}]\cdot[\int_0^{x(\alpha)} \beta f(\beta)d\beta] + [x(\alpha)]\cdot[x(\alpha)\cdot f(x(\alpha))\frac{\partial x}{\partial \alpha}]) \\
&+ [x(\alpha)^2]\cdot[f(x(\alpha))\frac{\partial x}{\partial \alpha}] \\
&= 2x(\alpha)\cdot\frac{\partial x}{\partial \alpha}]\cdot\int_0^{x(\alpha)} f(\beta)d\beta \\
&+ 2\frac{\partial x}{\partial \alpha}]\cdot\big([x(\alpha)^2]\cdot f(x(\alpha)) - [x(\alpha)^2]\cdot f(x(\alpha))\big) \\
&- 2\frac{\partial x}{\partial \alpha}]\int_0^{x(\alpha)} \beta f(\beta)d\beta \\
&= 2\cdot\frac{\partial x}{\partial \alpha}]\cdot[x(\alpha)\cdot\int_0^{x(\alpha)} f(\beta)d\beta - \int_0^{x(\alpha)} \beta f(\beta)d\beta] \\
&= 2\cdot\frac{\partial x}{\partial \alpha}]\cdot[x(\alpha)\cdot P(\beta\le x(\alpha)) - E[\beta|\beta\le x(\alpha)]\cdot P(\beta\le x(\alpha))] \\
&= 2\cdot\frac{\partial x}{\partial \alpha}]\cdot[x(\alpha) - E[\beta|\beta\le x(\alpha)]]\cdot P(\beta\le x)
\end{aligned}$$

## C.2 Optimization in Money Market Department

### *C.2.1 Approximation of Cash Flow SDE by Binomial Cash Flow Model*

According to section 6.1 Money Market manages the following cash flow on a daily basis:

$$
\begin{aligned}
CF_{t_i}^{MMD} &= \underbrace{\mu \cdot \Delta t}_{\substack{\text{Deterministic Cash Flow} \\ \text{Next Quarter}}} + \underbrace{\sigma^A \cdot \Delta W_{t_i}^A}_{\text{Brownian Component}} \\
CF_0 &: \text{ given}
\end{aligned}
\tag{C.4}
$$

The balance (cumulated cash flow) of (C.4) writes as:

$$
\begin{aligned}
B_0 &= CF_0 \\
B_{t_{k+1}} &= CF_0 + \sum_{i=1}^{k+1} CF_{t_i} \\
&= B_{t_k} + CF_{t_{k+1}} \\
&= B_{t_k} + \mu \cdot \Delta t + \sigma^A \cdot \Delta W_{t_{k+1}}^A
\end{aligned}
\tag{C.5}
$$

(C.5) is normally distributed. We approximate (C.5) with the following binomial model:

$$
\begin{aligned}
B_0 &= CF_0 \\
B_{t_{k+1}} &= B_{t_k} + CF_{t_{k+1}} \\
&= B_{t_k} + \begin{cases} CF^+, & P(CF_t = CF^+) = p \\ CF^-, & P(CF_t = CF^-) = 1 - p \end{cases}
\end{aligned}
\tag{C.6}
$$

We assume that cash flows of different time points are independent.

The resulting binomial tree is displayed in figure C.1. Instead of an infinite number of possible cash flows, only two cash flows are possible: an inflow of $CF^+$ at probability $p$ and an outflow of $CF^-$ at probability $(1-p)$. The probabilities are constant. The cash flow at $t_0$ is given.

In the following, we map $CF^+$ and $CF^-$ to the parameter $\mu$ and $\sigma$ of the original cash flow process (C.4).

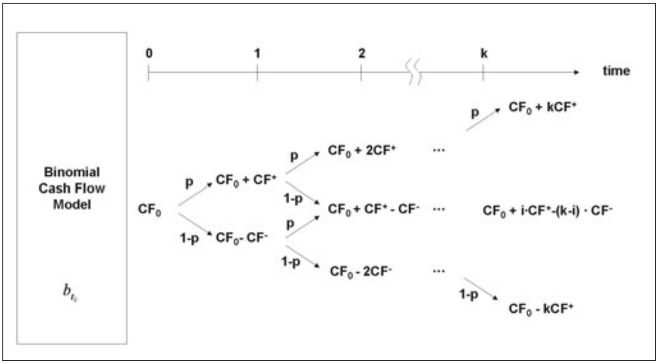


**Fig. C.1** Model Dynamic as Binomial Tree

Obviously, a particular realization $b^i_{t_k}$ of (C.6) can be written as:

$$
\begin{aligned}
b_0 &= CF_0 \\
b^i_{t_k} &= CF_0 + i \cdot CF^+ - (k-i) \cdot CF^- \\
&= CF_0 + i \cdot (CF^+ + CF^-) - k \cdot CF^-
\end{aligned}
$$

Being:

$i$ : Number of up-steps

$k$ : Number of time steps

$i \sim Bin(k, p)$

We want to determine $CF^+$ and $CF^-$ such that the de-leveled binomial approximation $(b^i_{t_k} - CF_0)$ matches expectation and variance of the de-leveled original process (C.5).

$$
\begin{aligned}
E[b_{t_k} - CF_0] &\stackrel{!}{=} E[B_{t_k} - CF_0] = k\mu\Delta t \\
Var[b_{t_k} - CF_0] &\stackrel{!}{=} Var[B_{t_k} - CF_0] = \sigma^2 k\Delta t
\end{aligned}
$$

We have:

$$
\begin{aligned}
E[b_{t_k}] &= E[i \cdot CF^+ - (k-i) \cdot CF^-] \\
&= E[i \cdot (CF^+ + CF^-) - k \cdot CF^-] \\
&= (CF^+ + CF^-)E[i] - k \cdot CF^- \\
&= (CF^+ + CF^-)k \cdot p - k \cdot CF^- \stackrel{!}{=} k\mu\Delta t &\text{(C.7)} \\
Var[b_{t_k}] &= Var[i \cdot (CF^+ + CF^-) - k \cdot CF^-] \\
&= (CF^+ + CF^-)^2 \cdot Var[i] \\
&= (CF^+ + CF^-)^2 \cdot kp(1-p) \stackrel{!}{=} \sigma^2 k \cdot \Delta t &\text{(C.8)}
\end{aligned}
$$

From (C.7), we get:

$$
\begin{aligned}
(CF^+ + CF^-)k \cdot p - k \cdot CF^- &\stackrel{!}{=} k\mu\Delta t \\
&\Leftrightarrow \\
(CF^+ + CF^-) \cdot p - CF^- &\stackrel{!}{=} \mu\Delta t \\
CF^- &= \frac{p \cdot CF^+ - \mu\Delta t}{1-p} &\text{(C.9)}
\end{aligned}
$$

Substituting $CF^-$ in (C.8) yields:

$$
\begin{aligned}
(CF^+ \frac{p \cdot CF^+ - \mu\Delta t}{1-p})^2 \cdot kp(1-p) &\stackrel{!}{=} \sigma^2 k \cdot \Delta t \\
&\Leftrightarrow \\
p(1-p)[\frac{CF^+ - CF^+ p + CF^+ p - \mu\Delta t}{1-p}] &= \sigma^2 \Delta t \\
CF^+ &= \sqrt{\frac{\sigma^2 \Delta t(1-p)}{p}} + \mu\Delta t
\end{aligned}
$$

Setting $p = \frac{1}{2}$, we obtain:[2]

$$
CF^+ = \sigma\sqrt{\Delta t} + \mu\Delta t
$$

Using (C.9), $CF^-$ writes as:

$$
\begin{aligned}
CF^- &= \frac{p \cdot (\sigma\sqrt{\Delta t} + \mu\Delta t) - \mu\Delta t}{1-p} \\
&= \sigma\sqrt{\Delta t} - \mu\Delta t
\end{aligned}
$$

[2] The probability is a free parameter. See [Schmidt, 1997].

Finally, we obtain the binomial approximation $b_{t_k}$:

$$b_0 = CF_0$$
$$b_{t_k} = b_{t_{k-1}} + \begin{cases} CF^+, & P[CF_{t_k} = CF^+] = \frac{1}{2} \\ -CF^-, & P[CF_{t_k} = CF^-] = \frac{1}{2} \end{cases}$$

Being:

$$CF^+ = f(\mu, \sigma) = \sigma\sqrt{\Delta t} + \mu\Delta t$$
$$CF^- = g(\mu, \sigma) = \sigma\sqrt{\Delta t} - \mu\Delta t$$

### *C.2.2 Determination of Optimality Candidates*

Within this section, we verify whether the optimal decisions $d_{12}[i,j]$ are always finite. In particular, we check whether the optimum of unbounded intervals $[-\infty, k]$ or $[l, +\infty]$ is the lower/ higher well-defined interval boundary. We start with node [1,1].

The maximum is determined by following the derivation into the positive direction to the end of the interval.

For the derivation of (6.41) w.r.t. $d_{1,2}[1,1]$ only expressions containing $d_{1,2}[1,1]$ are of interest. Splitting up the value function into $d_{1,2}[1,1]$ expressions and a constant c leads to (C.10).

$$\begin{aligned}
f(d_{1,2}[1,1]) = \\
& p^{CF}(1-p^c)\cdot( \\
& ([CF_0 + CF^+ - d_{02} - d_{12}[1,1]]^+ + 2\cdot[d_{12}[1,1]]^+)r^+ \\
& +([CF_0 + CF^+ - d_{02} - d_{12}[1,1]]^- + 2\cdot[d_{12}[1,1]]^-)r^- \\
& +p^{CF}(1-p^c)\cdot((([CF_0 + CF^+ + CF^+ - d_{12}[1,1]]^+)r^+ \\
& +([CF_0 + CF^+ + CF^+ - d_{12}[1,1]]^-)r^-) \\
& +p^{CF}p^c\cdot((([CF_0 + CF^+ + CF^+ - d_{12}[1,1]]^+)r^+ \\
& +([CF_0 + CF^+ + CF^+ - d_{12}[1,1]]^-)r^{--}) \\
& +(1-p^{CF})(1-p^c)\cdot((([CF_0 + CF^+ - CF^- - d_{12}[1,1]]^+)r^+ \\
& +([CF_0 + CF^+ - CF^- - d_{12}[1,1]]^-)r^-) \\
& +(1-p^{CF})p^c\cdot((([CF_0 + CF^+ - CF^- - d_{12}[1,1]]^+)r^+ \\
& +([CF_0 + CF^+ - CF^- - d_{12}[1,1]]^-)r^{--}) \\
& +c)
\end{aligned} \tag{C.10}$$

We observe that $d_{12}[1,1]$ appears in 3 expressions (A,B,C):

$$\begin{aligned}
A :& [CF_0 + CF^+ - d_{02} - d_{12}[1,1]]^{+/-} \\
& \leftrightarrow CF_0 + CF^+ - d_{02} - d_{12}[1,1] \gtrless 0 \\
B :& [d_{12}[1,1]]^{+/-} \\
& \leftrightarrow d_{12}[1,1] \gtrless 0 \\
C :& [CF_0 + CF^+ + CF^+ - d_{12}[1,1]]^{+/-} \\
& \rightarrow CF_0 + CF^+ + CF^+ < d_{12}[1,1] \\
& [CF_0 + CF^+ - CF^- - d_{12}[1,1]]^{+/-} \\
& \rightarrow CF_0 + CF^+ - CF^- > d_{12}[1,1]]
\end{aligned}$$

The expressions can be positive and negative leading to eight possible cases that are displayed as 'case tree' in figure C.2. The structure of figure C.2 can be seen at the left margin in form of blocks. The blocks A-C refer to the expressions A-C. Each expression can be either positive or negative. The blocks A',...,C' refer to their derivations with respect to $d_{12}[1,1]$. The block 'Max' states the condition for a maximum, i.e. $\frac{\partial()}{\partial d_{12}[1,1]} > 0$. If the condition is fulfilled, the optimal $d_{12}[1,1]$ is the highest value of the interval noted 'D'. Otherwise, it is the lowest interval value noted 'd'. For case '1', the optimal value is the maximum value if the crisis probability is lower than $\frac{r^- - r^+}{r^- - r^{--}}$. This can not to be as $r^- - r^{--}$ is negative but probabilities are always positive. Hence, for this case, the maximizing value is the interval minimum. For case '2', we obtain that the objective value is independent on $d_{1,2}[1,1]$ allowing every value within the interval to be optimal.

Figure C.3 charts the case tree from figure C.2, the intervals and optima across $d_{1,2}[1,1]$. The interval boundaries $CF_0 + CF^+ - CF^-$ and $CF_0 + CF^+ + CF^+$ can lay around zero (= block I), can both be negative (= block II) and/ or both be positive (= block III). The situation relative to zero is important as at zero, the weights (= interest rates) in the value function change: positive amounts are invested at $r^+$, negative amounts are funded at $r^-$ or at $r^{--}$. The link between figure C.2 and figure C.3 is as follows: the block C of figure C.2 tells us the cases where $d_{1,2}[1,1]$ is beyond $CF_0 + CF^+ + CF^+$. These are cases No 1,5 and 3,7. In figure C.2, 1,5 and 3,7 are in different B-blocks, i.e. $d_{1,2}[1,1]$ is positive for 1,5 and negative for 3,7. Therefore, in figure C.3, 1,5 is in block I ('0' separates $CF_0 + CF^+ + CF^+$ and $CF_0 + CF^+ - CF^-$) and 3,7 in block II (both values are negative). We have chosen the outside intervals that have one unbounded interval limit. Figure C.3 clearly shows that the optimal value lays on the well-defined interval limit but does not go to infinity.

We first discuss block I: for decision values smaller than $CF_0 + CF^+ - CF^-$, the optimal decision is the minimum value, i.e. the interval boundary. For decision values larger than $CF_0 + CF^+ + CF^+$, the optimal decision is the maximum value, i.e. the interval boundary. For the special case that both boundaries are negative (block II)[3], there is the subcase that $d_{12}[1,1]$ is negative. For those cases (cases 3 and 7), the optimal values are the minimum

[3] This might be the case for a small starting balance $CF_0$ that cannot be overcompensated by cash inflows, e.g. $CF_0 + CF^+ + CF^+ = -20 + 5 + 5 = -10 < 0$.

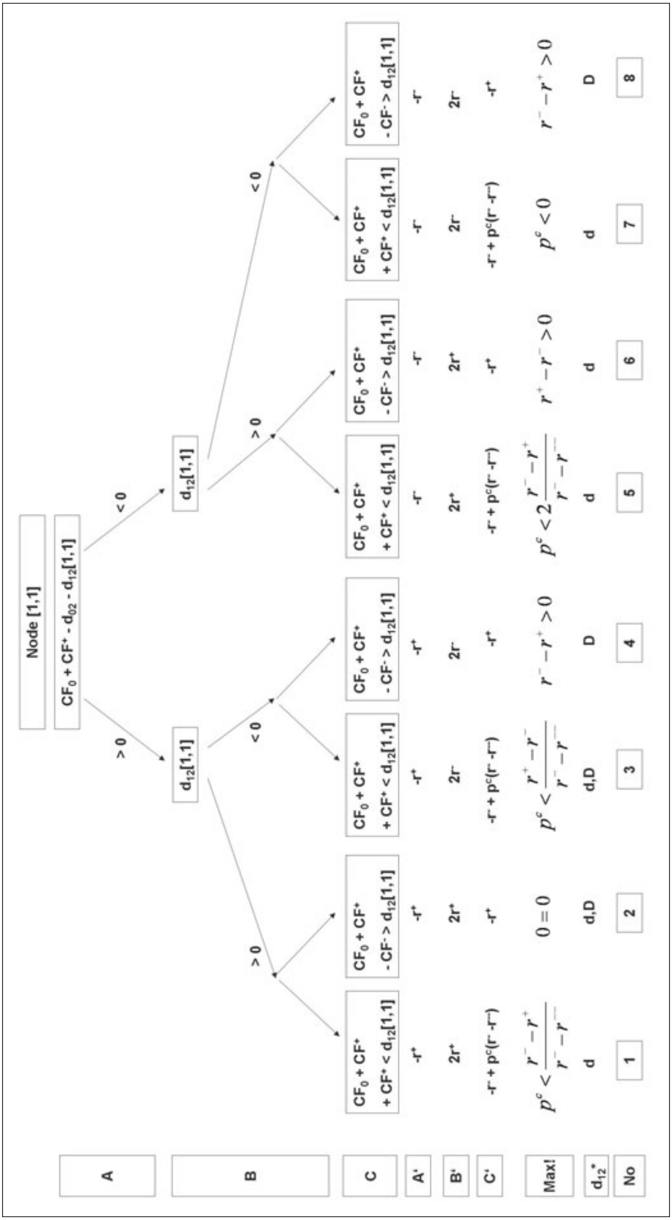


**Fig. C.2** Relevant Constellation for Node [1,1]

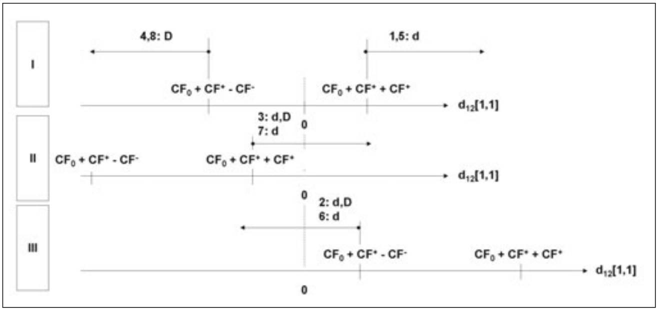


**Fig. C.3** Decision Regions and Optima, Node $d_{12}[1,1]$

and maximum value (case 3) or the minimum value (case 7). The maximum value of case 3 is somewhat disturbing, as this seems to lead to an unbounded decision. However, at the critical value 0, case 3 converts to case 1 ($d_{1,2}[1,1]$ becomes positive) and the optimal value for case 1 is a minimum, here 0. Thus, a bounded solution exists also for this setup. An optimal value of zero is plausible as it means that the optimal decision is 'no reserve'. In contrast, by only considering the two positive boundaries we would exclude the possibility of 'no reserve'.

For the setup that both boundaries are positive (Block III), both cases include the minimum value as optimal. However, as cases 4 and 8 (Block I) indicate, at zero the optimality changes and the maximum value (i.e. 0) is optimal.

As unbounded solutions do not exist, candidates for optimal $d_{12}[1,1]$ are the corner values:

$$d^*_{12}[1,1] \in \{CF_0 + CF^+ + CF^+, CF_0 + CF^+ - CF^-, 0\}$$

We verify the boundedness for node $d_{12}[1,2]$ the same way. Node [1,1] and [1,2] only differ in the funding conditions (node [1,1]: normal funding at $r^-$, node [1,2]: crisis funding at $r^{--}$). The funding rates in block A' and B' are changed from $r^-$ to $r^{--}$ (see figure C.4). This slightly changes conditions, but only in case 7 it also changes the optimium to the maximum value. However, as argued, the optimium changes at '0' to a minimum (here: zero) which makes the problem bounded again. Hence, we confirm the boundedness of the optimization and $d_{12}[1,2]$ has the same optimal candidates as node [1,1].

The boundedness for nodes [2,1] and [2,2] can be argued the same way: the intervals of [2,i] and [1,i] only differ in their levels, but not their signs:

$$\text{level[1,i]} : CF_0 + CF^+ + / - CF^{+/-}$$
$$\text{level[2,i]} : CF_0 - CF^- + / - CF^{+/-}$$
$$\text{level[1,i]} : - \text{level[2,i]} = CF^+ + CF^-$$

The level difference only affects the (absolute) location of the intervals, but not the derivatives. As we already checked all possible interval configurations (0 included/ left-/ right-

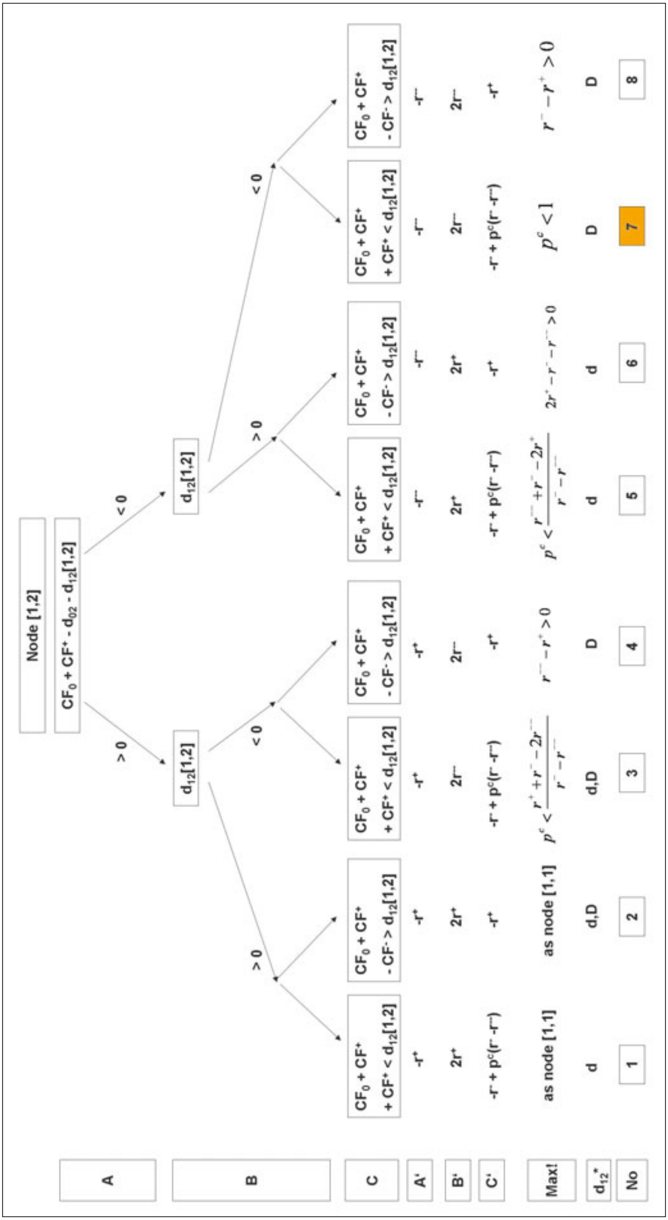


**Fig. C.4** Possible Cash Flow Setups

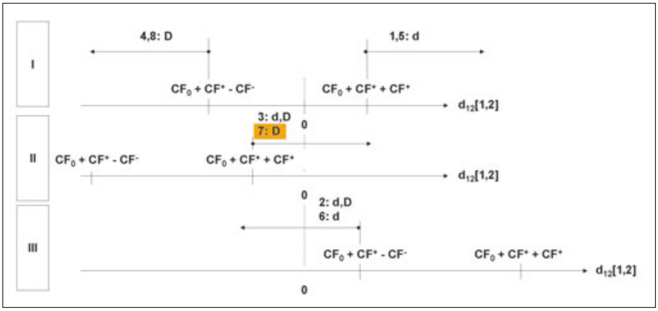


**Fig. C.5** Decision Regions and Optima, Node $d_{12}[1,2]$

sided from interval) and the derivatives remain the same, the analysis would lead to the same results but at a modified level: in node [2,i] instead of $CF_0 + CF^+ + CF^+$ as in node [1,i], we have $CF_0 + CF^+ - CF^-$. And instead of $CF_0 + CF^+ - CF^-$ we have $CF_0 - CF^- - CF^-$. Hence, for $d_{12}[2,i]$ we obtain as optimal candidates:

$$d^*_{12}[1,1] \in \{CF_0 - CF^+ + CF^+, CF_0 - CF^+ - CF^-, 0\}$$

Till now we have checked the existence of an optimal strategy for $d_{12}[i,j]$ and determined the candidates. However, we also have to check for the existence of an optimal $d_{02}$.

### *C.2.2.1 Candidates for t0*

The objective function where all non-$d_{02}$-elements are summarized in a constant c is given by (C.11).

$$\begin{aligned}
\max_{d_{02},d_{12}[i,j]} & ([CF_0 - d_{02}]^+ + 2\cdot[d_{02}]^+)r^+ + ([CF_0 - d_{02}]^- + 2\cdot[d_{02}]^-)r^- \\
& + p^{CF}(1-p^c)\cdot((([CF_0 + CF^+ - d_{02} - d_{12}[1,1]]^+)r^+ \\
& + ([CF_0 + CF^+ - d_{02} - d_{12}[1,1]]^-)r^-) \\
& + p^{CF}p^c\cdot((([CF_0 + CF^+ - d_{02} - d_{12}[1,2]]^+)r^+ \\
& + ([CF_0 + CF^+ - d_{02} - d_{12}[1,2]]^-)r^{--}) \\
& + (1-p^{CF})(1-p^c)\cdot((([CF_0 - CF^- - d_{02} - d_{12}[2,1]]^+)r^+ \\
& + ([CF_0 - CF^- - d_{02} - d_{12}[2,1]]^-)r^-) \\
& + (1-p^{CF})p^c\cdot((([CF_0 - CF^- - d_{02} - d_{12}[2,1]]^+)r^+ \\
& + ([CF_0 - CF^- - d_{02} - d_{12}[2,1]]^-)r^{--}) \\
& + c)
\end{aligned} \tag{C.11}$$

Substituting the $d_{12}[i,j]$-candidates, we obtain:

$$\begin{aligned}
\max_{d_{02},d_{12}[i,j]} & ([CF_0-d_{02}]^+ + 2\cdot[d_{02}]^+)r^+ + ([CF_0-d_{02}]^- + 2\cdot[d_{02}]^-)r^- \\
& +(p^{CF}(1-p^c)\cdot((([CF_0+CF^+-d_{02}]^+)r^+ \\
& \quad +([CF_0+CF^+-d_{02}]^-)r^- + s))\cdot 1_{\{d_{12}[1,1]=0\}} \\
& +(p^{CF}(1-p^c)\cdot((([-CF^+-d_{02}]^+)r^+ \\
& \quad +([-CF^+-d_{02}]^-)r^- + s))\cdot 1_{\{d_{12}[1,1]=CF_0+CF^++CF^+\}} \\
& +(p^{CF}(1-p^c)\cdot((([CF^--d_{02}]^+)r^+ \\
& \quad +([CF^--d_{02}]^-)r^- + s))\cdot 1_{\{d_{12}[1,1]=CF_0+CF^+-CF^-\}} \\
& +(p^{CF}p^c\cdot((([CF_0+CF^+-d_{02}]^+)r^+ \\
& \quad +([CF_0+CF^+-d_{02}]^-)r^{--} + s))\cdot 1_{\{d_{12}[1,2]=0\}} \\
& +(p^{CF}p^c\cdot((([-CF^+-d_{02}]^+)r^+ \\
& \quad +([-CF^+-d_{02}]^-)r^{--} + s))\cdot 1_{\{d_{12}[1,2]=CF_0+CF^++CF^+\}} \\
& +(p^{CF}p^c\cdot((([CF^--d_{02}]^+)r^+ \\
& \quad +([CF^--d_{02}]^-)r^{--} + s))\cdot 1_{\{d_{12}[1,2]=CF_0+CF^+-CF^-\}} \\
& +((1-p^{CF})(1-p^c)\cdot((([CF_0-CF^--d_{02}]^+)r^+ \\
& \quad +([CF_0-CF^--d_{02}]^-)r^- + s))\cdot 1_{\{d_{12}[2,1]=0\}} \\
& +((1-p^{CF})(1-p^c)\cdot((([-CF^+-d_{02}]^+)r^+ \\
& \quad +([-CF^+-d_{02}]^-)r^- + s))\cdot 1_{\{d_{12}[2,1]=CF_0-CF^++CF^+\}} \\
& +((1-p^{CF})(1-p^c)\cdot((([CF^--d_{02}]^+)r^+ \\
& \quad +([CF^--d_{02}]^-)r^- + s))\cdot 1_{\{d_{12}[2,1]=CF_0-CF^--CF^-\}} \\
& +((1-p^{CF})p^c\cdot((([CF_0-CF^--d_{02}]^+)r^+ \\
& \quad +([CF_0-CF^--d_{02}]^-)r^{--} + s))\cdot 1_{\{d_{12}[2,2]=0\}} \\
& +((1-p^{CF})p^c\cdot((([-CF^+-d_{02}]^+)r^+ \\
& \quad +([-CF^+-d_{02}]^-)r^{--} + s))\cdot 1_{\{d_{12}[2,2]=CF_0-CF^++CF^+\}} \\
& +((1-p^{CF})p^c\cdot((([CF^--d_{02}]^+)r^+ \\
& \quad +([CF^--d_{02}]^-)r^{--} + s))\cdot 1_{\{d_{12}[2,2]=CF_0-CF^--CF^-\}}
\end{aligned} \tag{C.12}$$

As before, we want to check whether the optimal value of one-sided unlimited intervals ($d_{02}\in(\Xi,+\infty)$ is the well-defined boundary.

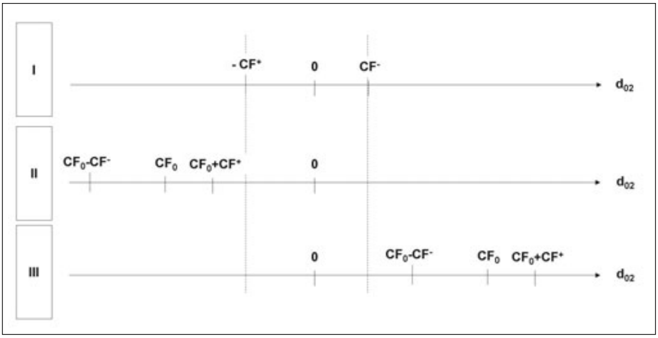


**Fig. C.6** Candidates for Unlimited Intervals of $d_{02}$

Based on (C.12), we obtain the following interval boundaries:

$$
\begin{aligned}
[CF_0 - d_{02}]^{+/-} &: d_{02} \gtrless CF_0 \\
[d_{02}]^{+/-} &: d_{02} \gtrless 0 \\
[CF_0 + CF^+ - d_{02}]^{+/-} &: d_{02} > CF_0 + CF^+ \\
[-CF^+ - d_{02}]^{+/-} &: d_{02} < -CF^+ < 0 \\
[CF_0 - CF^- - d_{02}]^{+/-} &: d_{02} < CF_0 - CF^- \\
[CF^- - d_{02}]^{+/-} &: d_{02} > CF^- > 0
\end{aligned}
$$

In order to determine the unlimited intervals, figure C.6 visualizes the previous interval boundaries. As $CF^-$ and $CF^+$ are assumed to be positive[4], $CF^-$ is a candidate for the interval $[\Xi, \infty]$ and $-CF^+$ a candidate for the interval $[-\infty, \xi]$ (see block I in figure C.6. It is obvious that zero can not be the interval boundary of an unlimited interval. It is always within the $[-CF^+, CF^-]$-interval. Therefore, we do not have to explicitly test for $d_{02} \gtrless 0$. Just like the interval $[-CF^+, CF^-]$ is situated around zero, we have a similar interval situated around $CF_0$: $[CF_0 - CF^-, CF_0 + CF^+]$. Depending on the situation of $CF_0$, its lower bound $CF_0 - CF^-$ is a candidate for the lower unbounded interval (see block II) whereas its upper bound $CF_0 + CF^+$ is a candidate for the upper unbounded interval (see block III).

[4] $CF^-$ is an outflow, because it is always used with a negative sign.

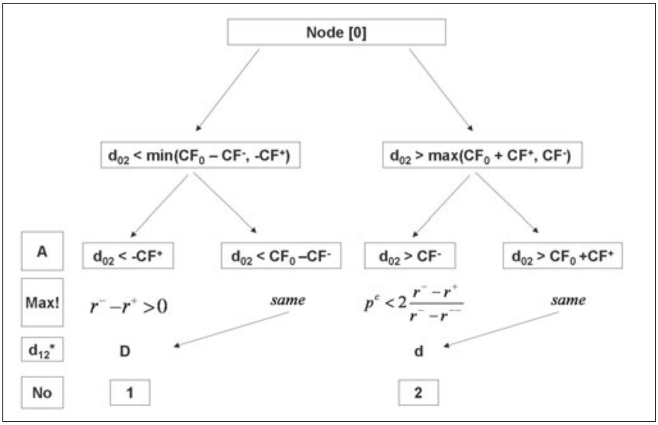


**Fig. C.7** Case Tree for Unlimited Intervals of $d_{02}$

We conclude that we have to check the derivations for $max(CF_0 + CF^+, -CF^-) < d_{02}$ and $d_{02} < min(-CF^+, CF_0 - CF^-)$. The resulting case tree summarizes figure C.7. It turns out that for the two possible ∞-intervals, the crisis probability has to be negative to have an infinity optimal $d_{02}$-value. Therefore, for all eligible crisis probabilities, the optimal value is the minimum in that interval, i.e. $d^*_{02} = CF^-$ or $d^*_{02} = CF_0 + CF^+$, respectively. For the $-\infty$-intervals, the maximum condition is always fulfilled. We can state that the optimal value is the maximum (interval boundary) $d^*_{02} = -CF^+$ or $d^*_{02} = CF_0 - CF^-$, respectively.

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