# Optimal Delay Allocation under High Flexibility Conditions during Demand-Capacity Imbalance

A theoretical approach to show the potential of the User Driven Prioritisation Process

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# Outline

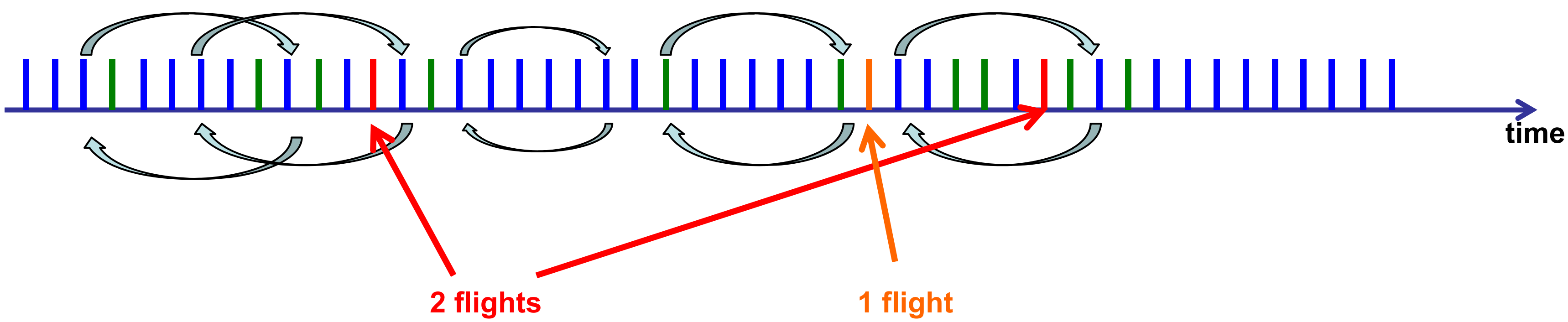
- Introduction, Motivation and Methodology
- Recall: Cost of delay and current UDPP features
- Problem of LVUCs and potential new UDPP features
- Flexibility vs. Equity
- Mathematical analysis and examples
- Conclusions and future work

# Introduction

- Profitability in air transport industry is **very sensitive to cost variations** (profit margins might be as low as 1-2%). [Ref: *IATA*]
- DCB protects well the safety and capacity performances by applying **delays in FPFS order when there is congestion at airports**. However, DCB has **no visibility of the impact of delay** on AUs operations.
- AUs would like further ***flexibility*** to reduce the ***'impact of delay'*** (cost of delay) during irregular operations.
- **User-driven approach could be a good solution to achieve efficiency** (while safety can be preserved) in the ATFM slot/delay allocation. [Ref: *Fundamental Theorem of Welfare*].

# How to give flexibility to AUs while not impacting negatively to others?

- User-Driven Prioritisation Process (**UDPP**) is being developed in the context of SESAR
- **Today, UDPP allows Enhanced Slot Swapping**, which gives flexibility to some AUs with no impact to others




- But, what about Low Volume Users in Constraint (**LVUC**), i.e., AUs with a few flights (e.g., 3 or less)

# Low Volume Users in Constraint (LVUCs)

- According to analysis of the last 20 AIRACs, **in the 85% of the hotspots the AUs have 3 flights or less** (they are LVUCs)

  ➔ **Limited flexibility** in these cases

- About in **2/3 of the regulations** the AUs will have **1 flight** operated in a hotspot

  ➔ **No flexibility with current UDPP**

- Some AUs are always LVUCs ➔ Problem of access

  ➔ It is **mandatory to give access to LVUCs** in UDPP

- Important: **any AU can be an LVUC** (quite often indeed)

# Motivation

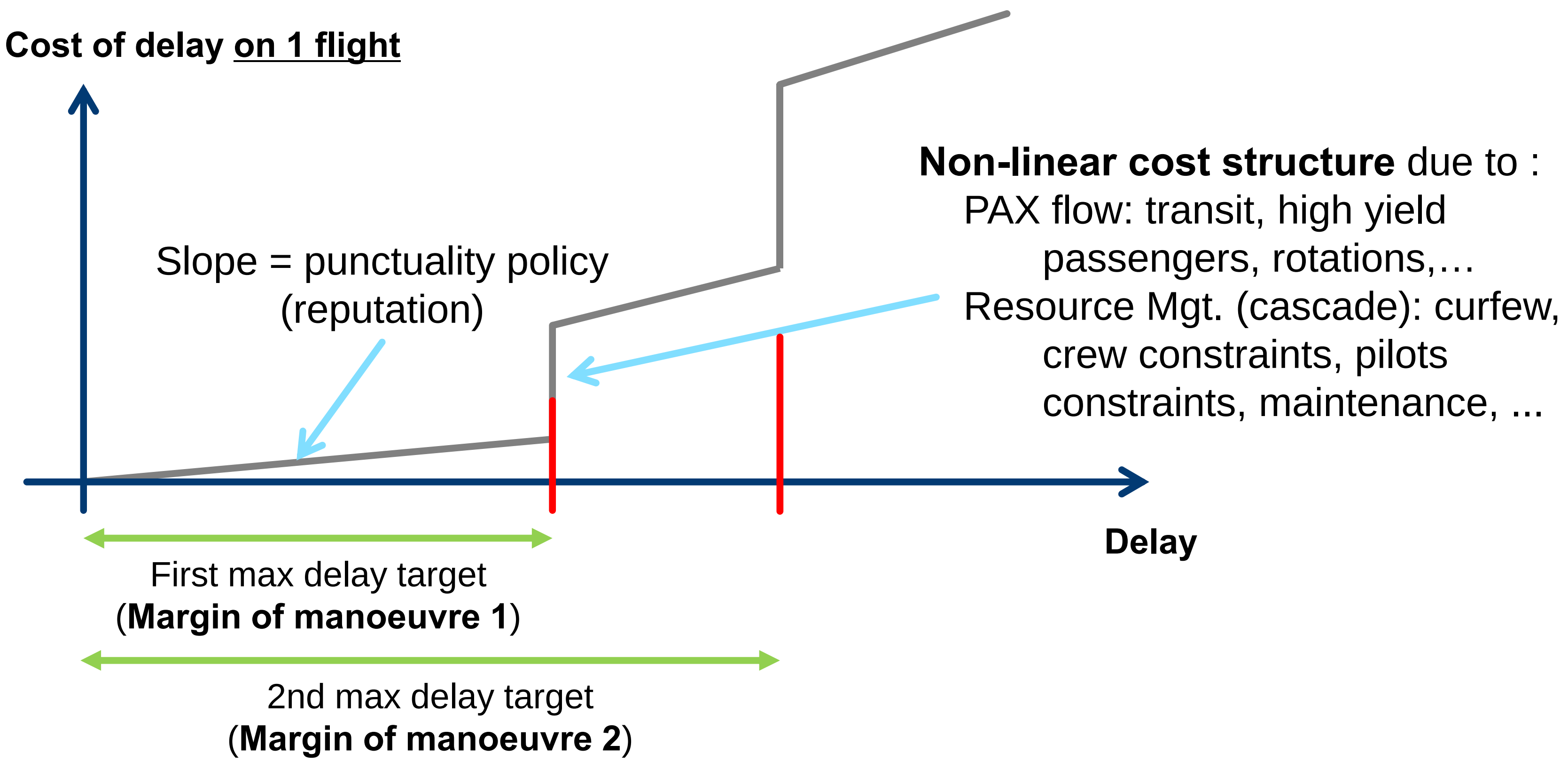
- With this presentation we want:
  - To explore the **limits of flexibility beyond the current UDPP** validated features (**to include LVUCs**).
  - To know what is the **dominant strategy of an AU when he can optimise** his cost of delay subject to equity constraints
  - To show that in theory we could have a **win-win situation if:**
    - **Slot exchange is allowed between AUs**
    - Each AU tries to **optimise their own cost of delay**
    - AUs are constrained by **equity** rules (‘*what is taken from others must be given back at some point*’)

# Methodology

- **High flexibility subject to equity** will be discussed.
- Via developing the ***User Delay Optimisation Model*** **(UDOM)** and analysing the results and implications
- Hypothetical case to study:
  - **The AU has high/full flexibility to transfer its total *baseline delay*** (i.e., initial ATFM delay) among his flights
  - For that purpose, the AU can **take flight sequence positions to other AUs (freely!)**
  - The AU is subject to a particular **equity** constraint: ***total baseline delay of the AU cannot be reduced***.

# Operational Cost of delay for Airspace Users ?

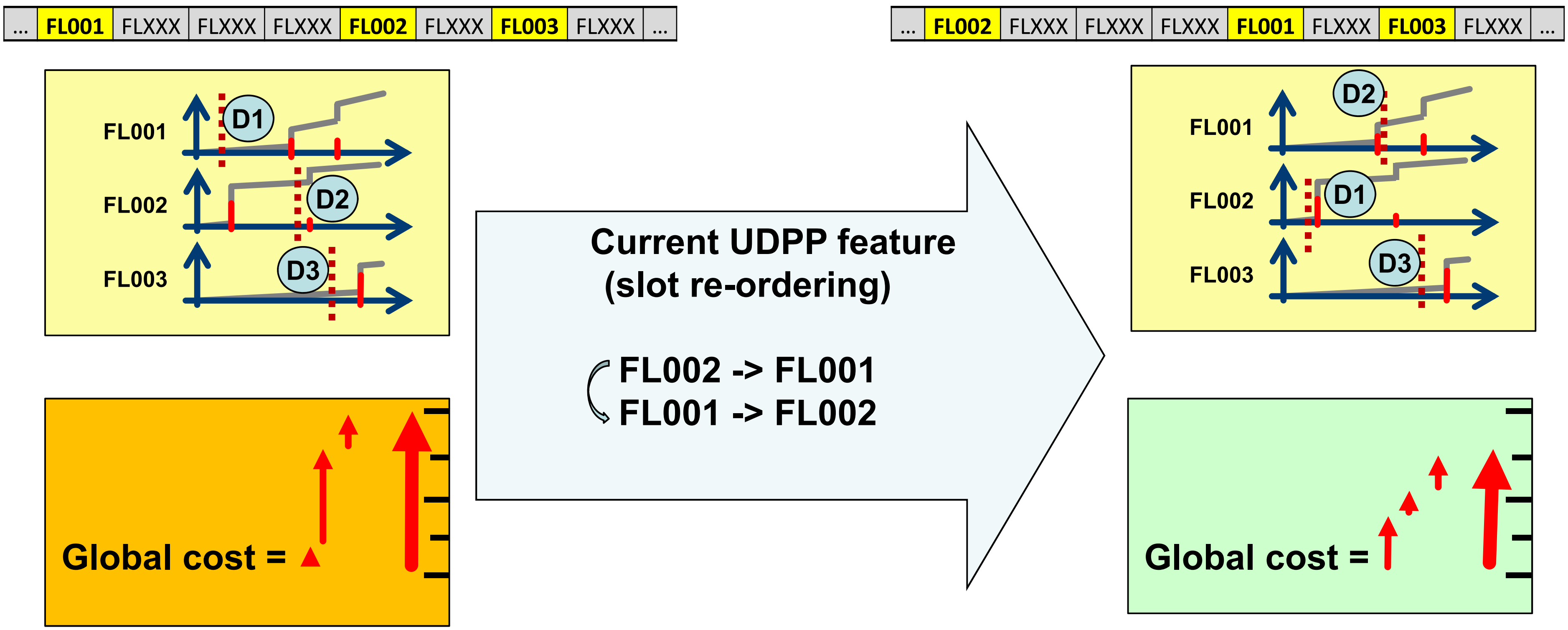
**From AU: No way to Act on Delay -> Act on Operational Cost of the Delay**




Each flight has its own particular complex cost structure only known by the AU

# Recall: Current UDPP

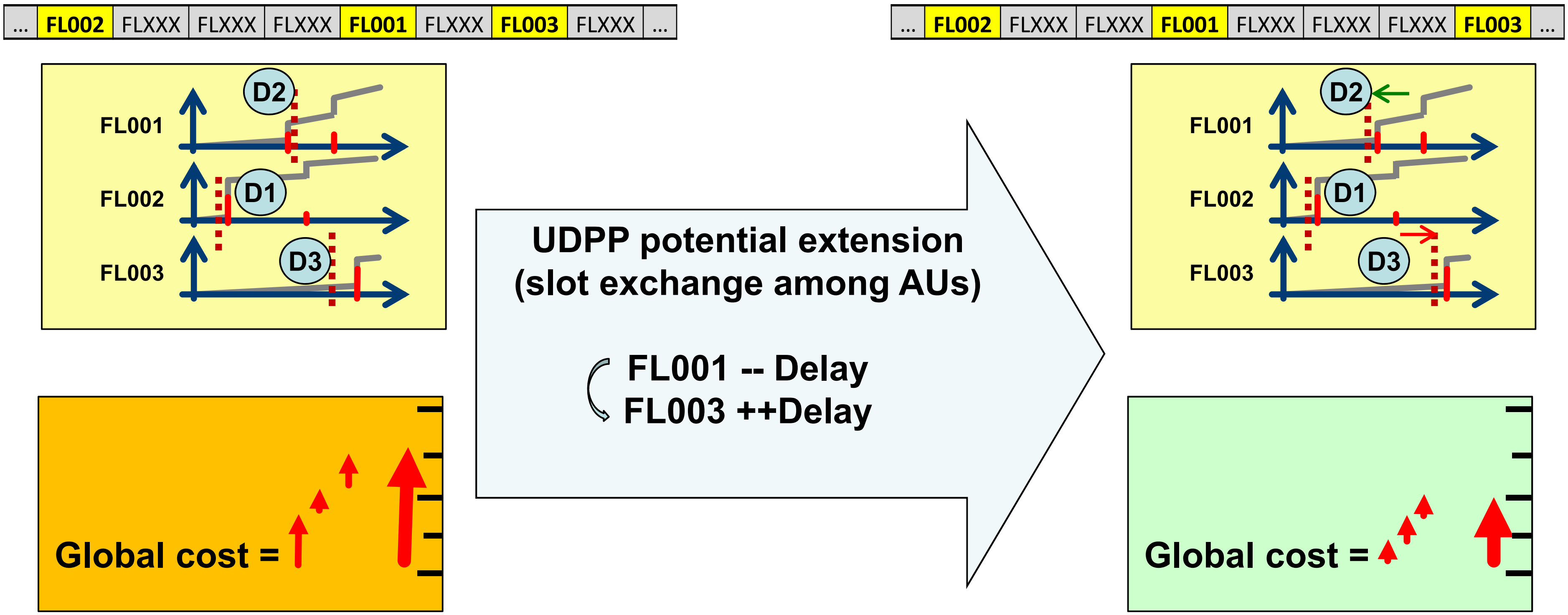
## UDPP Slot Swapping has demonstrated real benefits for AUs




In current UDPP flexibility is limited by the own number of flights in a hotspot and the re-scheduling limits(slots too far away are not feasible)

# Potential new advanced UDPP features

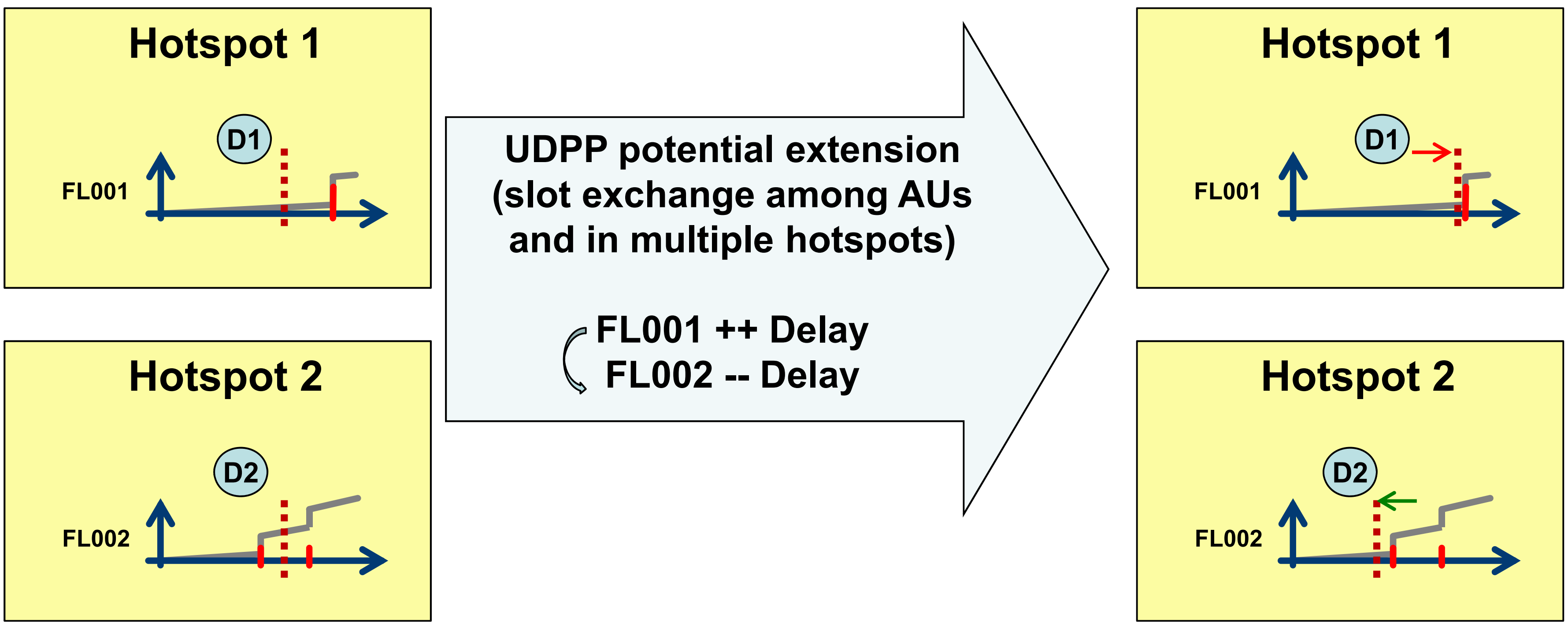
## The AU cannot improve the situation with current UDPP



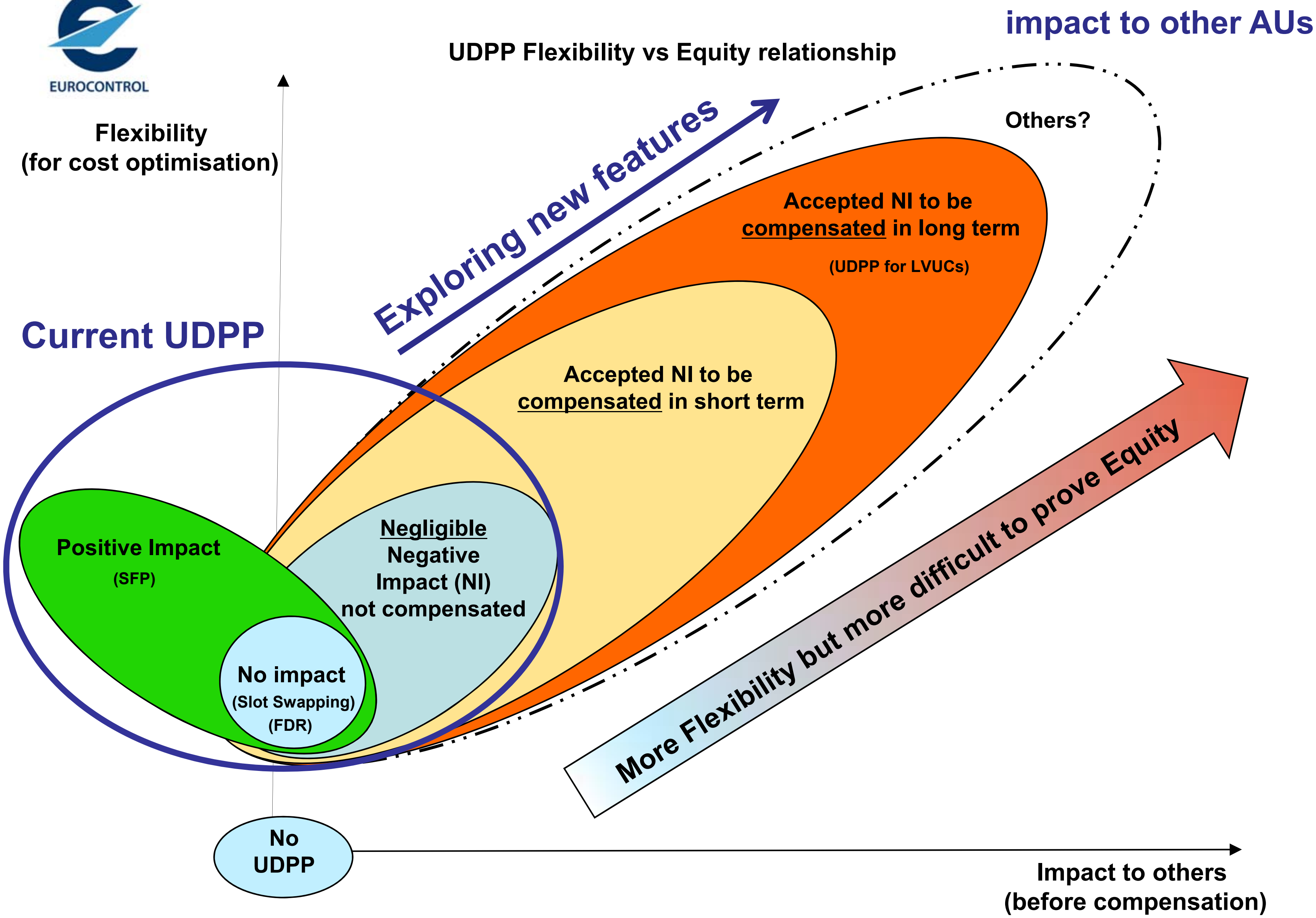

New advanced UDPP features are needed to give access to LVUCs and potentially to increase flexibility for everyone (**slot exchange between AUs**)

# LVUCs should have access throughout different hotspots

**The AU cannot improve the situation with current UDPP**

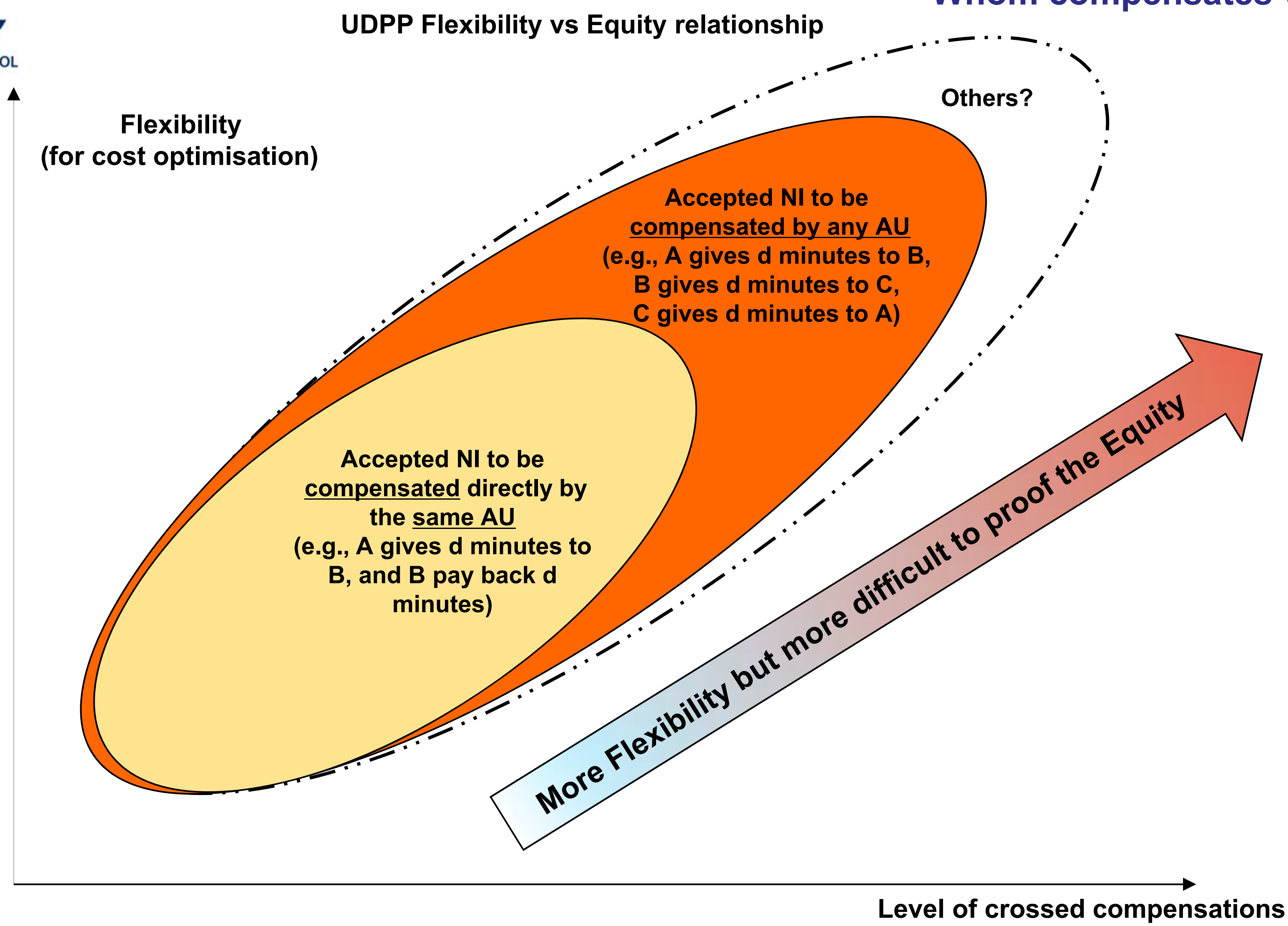



New advanced UDPP features are needed to give access to LVUCs (**slot exchange between AUs and possibly throughout multiple hotspots**)




**The higher the immediate impact to others and the longer the time for compensation, the more difficult to develop and validate an equitable UDPP method**

## Whom compensates whom?




**It might be more difficult to prove equity in case of crossed compensations among AUs (but more flexibility is expected).**

# USER DELAY OPTIMISATION MODEL (UDOM)

# Description of parameters

| Symbol | Range | Description |
| --- | --- | --- |
| $d$ | $[0,+\infty)$ | *Delay* of a flight ($d_0$ means $d=0$) |
| $U_0$ | $[0,+\infty)$ | Max *utility* of a flight when its $d=0$ |
| $N$ | $[0,+\infty)$ | Number of flights operated by an AU in the reference period |
| $\varepsilon_i$ | $(-\infty,+\infty)$ | *Elasticity* of the utility function of flight *i*. Used to simplistically characterise (continuous model) different operational flight margins |
| $\rho_i$ | $[0,1]$ | Probability of a flight *i* for being affected/delayed by a hotspot |
| $\delta_i$ | $[0,+\infty)$ | *Average delay expected* for flight *i* in the route operated (i.e., typical delay from hotspots on that route) |
| $\tilde{d}_i$ | $[0,+\infty)$ | *Baseline (random) delay* for flight *i* |
| $\tau_i$ | $(-\infty,+\infty)$ | *Delay shift,* to increase or reduce the delay of flight *i* |
| $d_i^*$ | $[0,+\infty)$ | *Optimal delay* for flight *i* in the actual hotspot |
| $d_i^{'}$ | $(-\infty,+\infty)$ | *Shifted delay*, i.e., delay difference between the optimal delay and the baseline delay, for flight *i* |

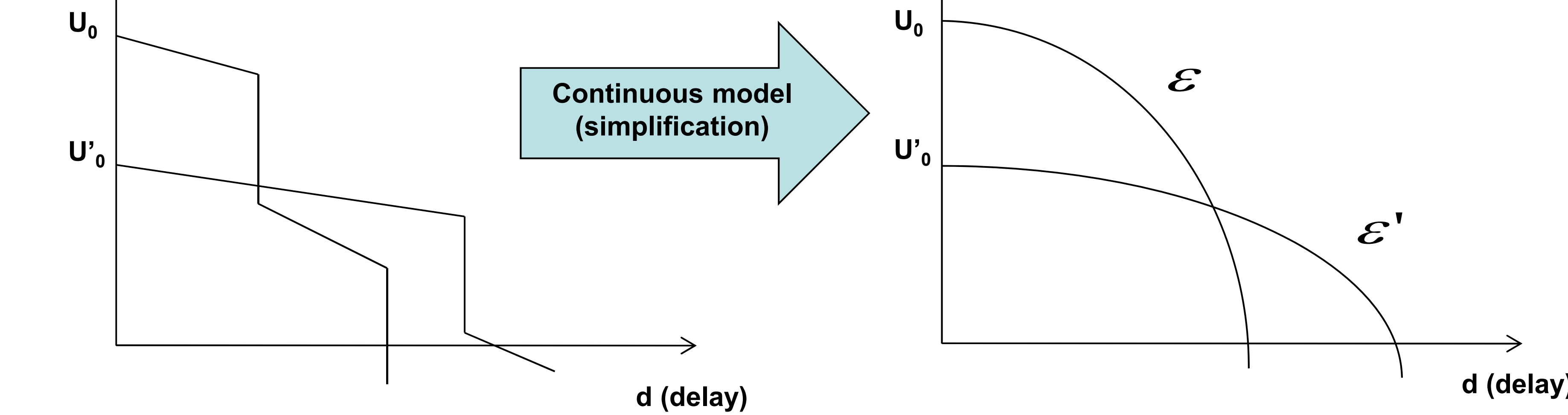
# UDOM: Utility of a flight

***Utility*** **can be understood as the value perceived by a particular AU if a given slot is allocated to a particular flight operated (directly related with the economic profits)**

**Different $U_0$ and $\varepsilon$ to model different carriers:**

$$U(d) = \tfrac{\varepsilon}{2} d^2 + U_0$$

$$\forall d \geq 0, U_0 > 0, \varepsilon < 0$$




**Utility = Profit – Delay Cost**

# UDOM: Utility of an AU

**Each AU will receive the utility of all its flights, the ones without delay and the ones with delay**

Sum of utilities of flights operated **without delay**

Sum of utilities of flights operated **with delay**

$$\bar{U} = \sum_{i=1}^{N} U_i(d_0)(1-\rho_i) + \sum_{i=1}^{N} U_i(\delta_i)\rho_i$$

Expected long-term utility for the AU

Delay = 0

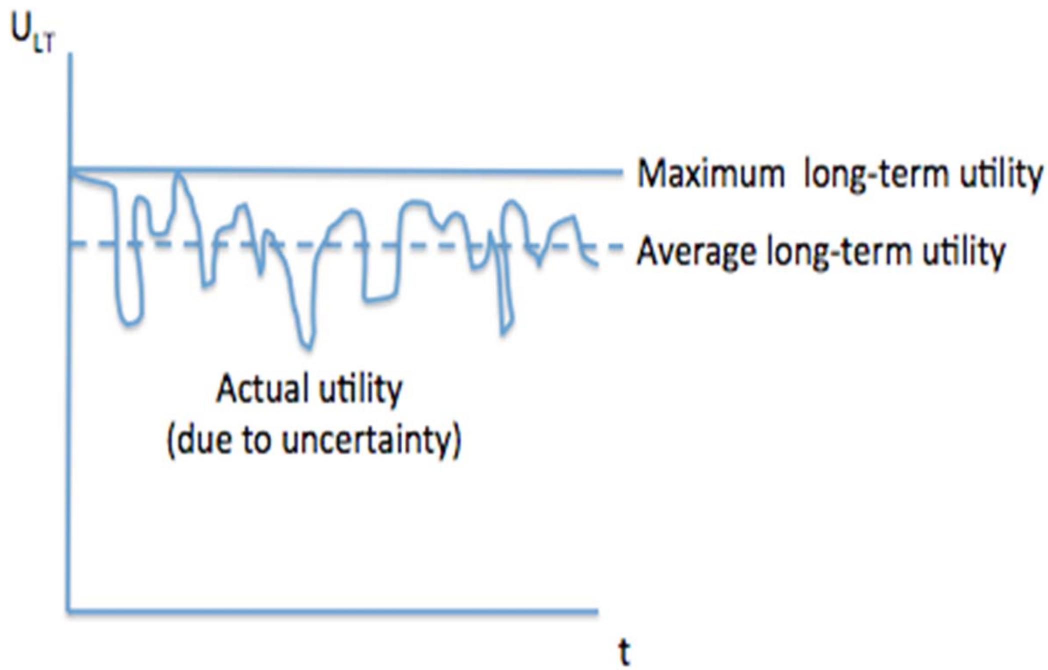
Probability of flight *i* of not being delayed

Average delay expected for flight *i*

Probability of flight *i* of being regulated and delayed

# UDOM: Utility of an AU

**The average long-term utility perceived by an AU will be <u>always below the ideal</u> case in which there is no delay**



# UDOM: Flexibility and Equity

***High Flexibility***: **in case of a hotspot, the AU would be allowed to freely change the delay of its flights with a *delay shift, τ***

$$U(d+\tau)=\tfrac{\varepsilon}{2}(d+\tau)^2+U_0$$

The *delay shift* is added to the baseline delay of a flight

***Equity:*** **to avoid potential system abuses, the model forces an equity constraint to AUs: baseline delay cannot be reduced**

$$\sum_{i=0}^{N}\tau_i=0$$

The sum of *delay shifts* must be zero

# UDOM: General optimisation model

**Under high flexible-equitable conditions an AU with *N flights* faces the following optimisation problem**

$$\max_{\tau_1,\ldots,\tau_N} \bar{U} = \sum_{i=1}^{N} U_i(d_0)(1-\rho_i) + \sum_{i=1}^{N} U_i(\delta_i + \tau_i)(\rho_i)$$

$$s.t. \left\{ \sum_{i=1}^{N} \tau_i = 0 \right.$$

*Flexibility: Delay shift* for each flight

*Equity constraint*

**Optimal Delay per flight:**

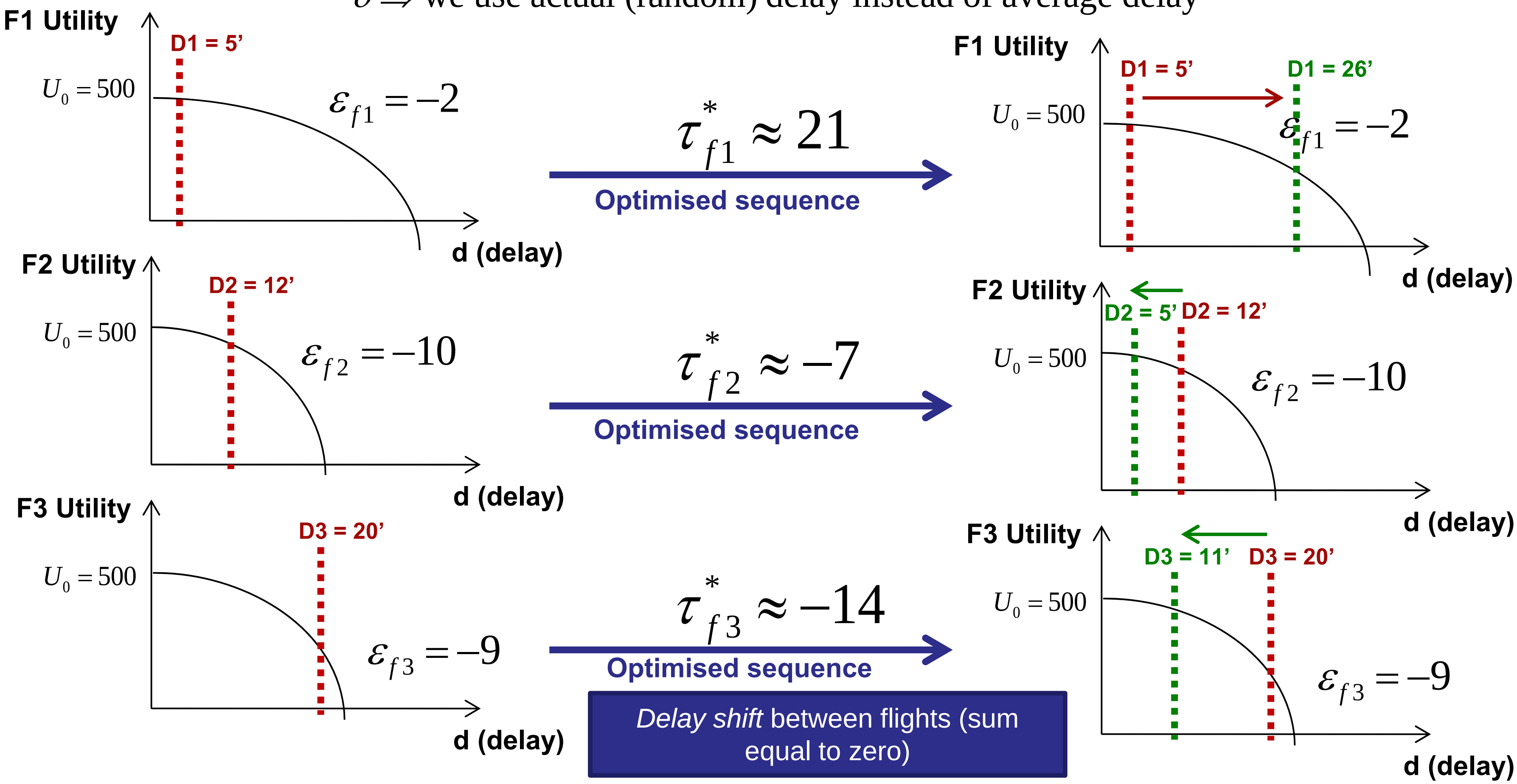
$$\tau_i^* = \frac{\sum_{j=1}^{N} \delta_j}{\sum_{j=1}^{N} \frac{\varepsilon_i \rho_i}{\varepsilon_j \rho_j}} - \delta_i$$

# UDOM: Example 1

## *Example*: LVUC with 3 flights in the same hotspot.

$\rho = 1$ (hotspot is actually happening)

$\delta \Rightarrow$ we use actual (random) delay instead of average delay



# UDOM: Example 1

**_Example_: LVUC with 3 flights in the same hotspot.**

**Baseline Utility:**

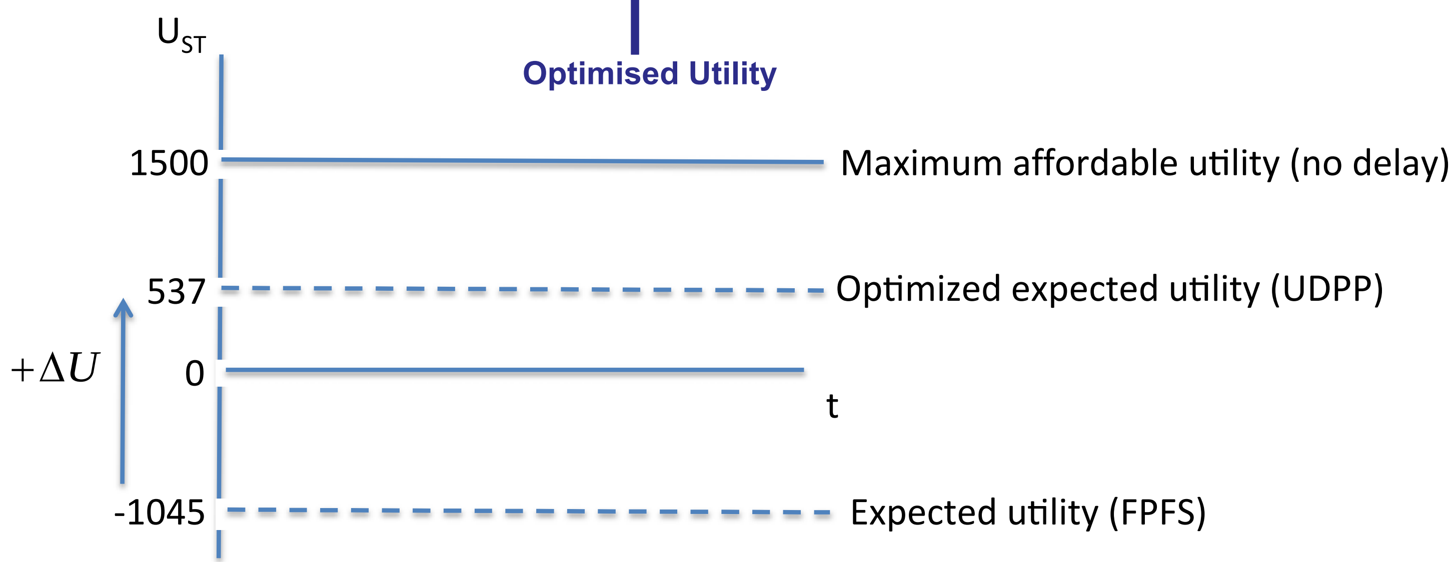
$$U_{BD} = U_{f1}(5) + U_{f2}(12) + U_{f3}(20) = 475 - 220 - 1300 = -1045$$

↑ Baseline Utility

**Optimised Utility:**

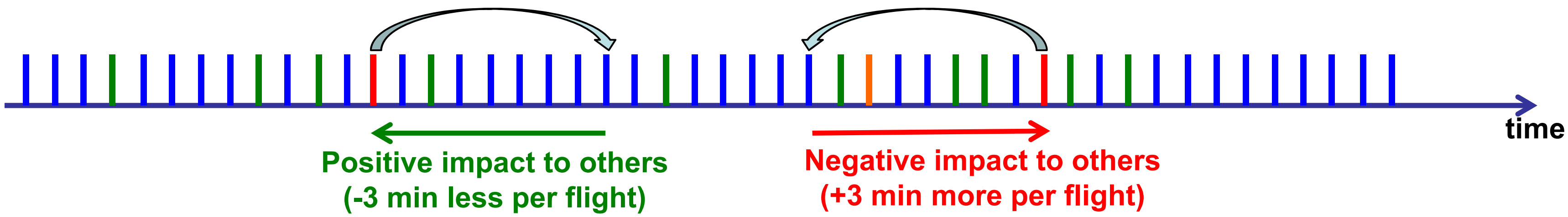
$$U^{*}_{UD} = U_{f1}(5+21) + U_{f2}(12-7) + U_{f3}(20-14) =$$
$$= -176 + 375 + 338 = +537$$

↑ Optimised Utility



# How to give flexibility to LVUCs?Case study of access to LVUCs

- Realistic scenario (simulated!): **HUB** (blue), **Low Cost** (green) and **LVUCs** (red and orange)




- With UDOM the LVUC1 (red) wants to **transfer 25 minutes** of delay from the second flight to the first one

- With the delay exchange LVUC1 could **save 30% of costs**

- LVUC2 (orange) with 1 flight only could use **User Delay Optimisation Model (UDOM) over the time** (multiple hotspots)

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# Realistic case study results

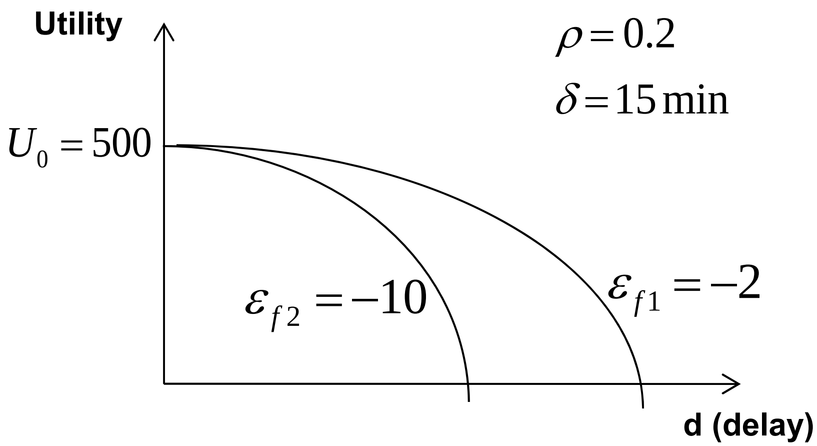
| AU name | Total flights | Baseline delay | Assigned delay | Difference |
|---|---|---|---|---|
| HUB | 52 | 1388 | 1373 | 15 |
| LC1 | 8 | 250 | 253 | -3 |
| LC2 | 12 | 461 | 470 | -9 |
| OA1 | 6 | 227 | 224 | 3 |
| OA2 | 2 | 32 | 32 | 0 |
| OA3 | 2 | 59 | 62 | -3 |
| OA4 | 1 | 33 | 33 | 0 |
| **LVUC1** | 3 | 94 | 94 | 0 |
| OA6 | 4 | 113 | 113 | 0 |
| OA7 | 0 | 0 | 0 | 0 |
| OA8 | 6 | 208 | 211 | -3 |
| | **98** | **2865** | **2865** | **0** |

| AU name | % flights | % B.Delay | % A.Delay | Difference | NIT |
|---|---|---|---|---|---|
| HUB | 54,17% | 48,45% | 47,92% | 1,08% | -3 |
| LC1 | 8,33% | 8,73% | 8,83% | -1,20% | -3 |
| LC2 | 12,50% | 16,09% | 16,40% | -1,95% | -3 |
| OA1 | 6,25% | 7,92% | 7,82% | 1,32% | 0 |
| OA2 | 2,08% | 1,12% | 1,12% | 0,00% | 0 |
| OA3 | 2,08% | 2,06% | 2,16% | -5,08% | -3 |
| OA4 | 1,04% | 1,15% | 1,15% | 0,00% | 0 |
| **LVUC1** | 3,13% | 3,28% | 3,28% | 0,00% | 0 |
| OA6 | 4,17% | 3,94% | 3,94% | 0,00% | 0 |
| OA7 | 0,00% | 0,00% | 0,00% | 0,00% | 0 |
| OA8 | 6,25% | 7,26% | 7,36% | -1,44% | -3 |

**Max extra delay per flight impacted by the LVUC1 actions**

# UDOM: Example 2

***Example*: two flights operated by an LVUC in different times. Probability of being delayed at this airport at that time = 0.2 Average delay at this airport and at that time = 15 min.**




$$\rho = 0.2$$

$$\delta = 15\,\text{min}$$

**Optimisation:**

$$\max_{\tau_{f1}} \bar{U} = \left[U_{f1}(d_0) + U_{f2}(d_0)\right](1-\rho) + \left[U_{f1}(\delta + \tau_{f1}) + U_{f2}(\delta - \tau_{f1})\right](\rho)$$

$$\tau^*_{f1} = 10;\ \tau^*_{f2} = -10$$

*Delay shift* between the two flights sums up zero

$$\bar{U}^* = 1000(0.8) + \left[U_{f1}(15+\tau^*) + U_{f2}(15-\tau^*)\right](0.2) =$$

$$= 1000(0.8) + \left(\tfrac{-2}{2}(25)^2 - \tfrac{-10}{2}(5)^2\right) = 850$$

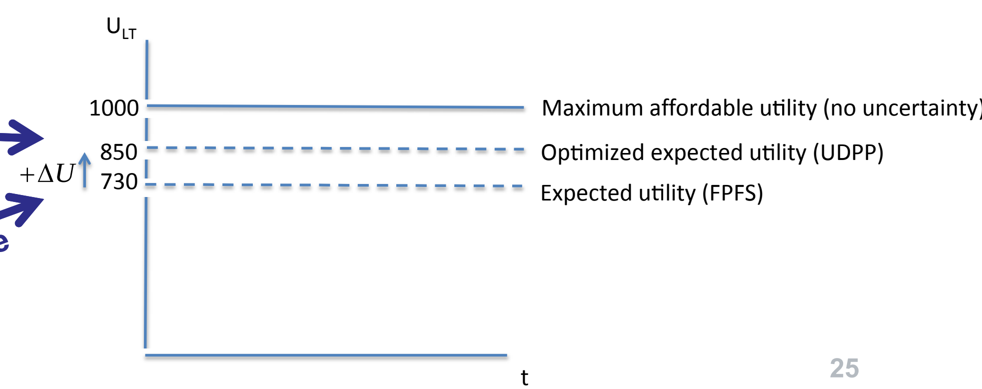
+10 ↑ ↑ -10

**Optimised sequence** →

$$\bar{U} = 1000(0.8) + \left(U_{f1}(15) + U_{f2}(15)\right)(0.2) =$$

$$= 1000(0.8) + \left(\tfrac{-2}{2}15^2 - \tfrac{-10}{2}15^2\right) = 730$$

**Baseline sequence** →



# Conclusions

- An hypothetical case has been studied with UDOM
- **High flexibility** has been given to an AU to minimise its own global delay costs. The AU had **full freedom to transfer delay** among its flights and to **take (freely) flight sequence positions from other AUs**.
- After imposing a **constraint of equity** (*total AU's delay must remain the same*), it is shown that:

a) There is an **optimal level of delay** for each flight ➔ **AUs would like to participate even if they are not obliged**.

b) The **equity condition increases flexibility** in the system (because the AU is forced to offer positions to other AUs ➔ *"Equity creates market"*)

c) If the number of LVUCs is not too large, the **impact to others might be negligible**

**d) Smooth coordination might be possible** with a reduced set of simple UDPP rules

e) AUs could be just **focused on optimising their own operations**

# Future work

- **Cost model and optimisation model will be updated** with more realistic curves.
- High Flexibility will be given to LVUCs while **co-existing with current UDPP features** (for non-LVUCs)
- More effort must be dedicated to develop validation scenarios (more difficult to **demonstrate equity in the long-term**)

**Any Questions ?**