Trust is good – optimal control tours are better! [1]

Elmar Swarat & *Thomas Schlechte*

EWG POR Workshop

Berlin, 2.11.2020

Bundesamt für Güterverkehr

ZIB

IVU TRAFFIC TECHNOLOGIES AG

[1] Доверяй, но проверяй! [Lenin(1914)]

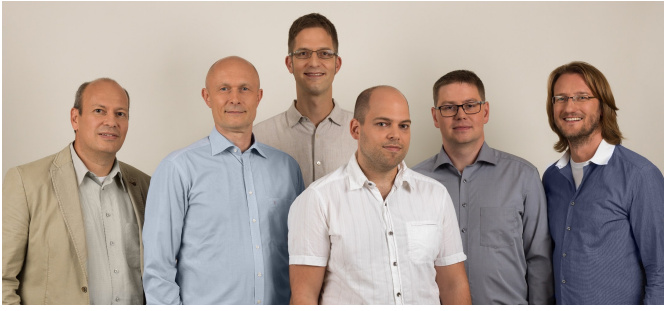
Outline

1. Who?
2. What & Why?
3. How?

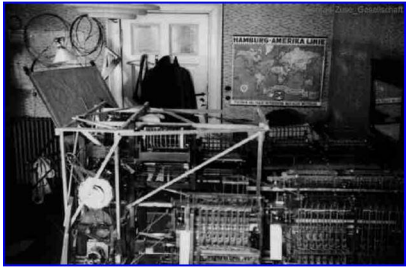
ZIB Spin-Off LBW since 2000

Mission

Development of high performance mathematical optimization modules for planning systems in mass transit, rail, and air transport.



Zuse Institute Berlin



(Public & Private) Toll-Team

Offense Line

- QB: Thomas Schlechte (LBW)
- Center: Elmar Swarat (ZIB)
- Tackle: Markus Reuther (LBW)
- Tackle: Christoph Auerbach (BAG)
- Guard: Ivanka Peneva (IVU)
- Running Back: Gert Schneider (BAG)
- Full Back: Ralf Borndörfer (ZIB)
- Tight End: Christof Schulz (LBW)
- Tight End: Torsten Klug (LBW)
- Wide Receiver: Stephan Schwartz (ZIB)
- Wide Receiver: Laura Stumpf (IVU)

ZIB

IVU TRAFFIC TECHNOLOGIES AG

LBW
Mathematical Optimization Systems in Public Transit

1. Who?
2. What & Why?
3. How?

The German Toll System for Trucks ($> 7.5t$)

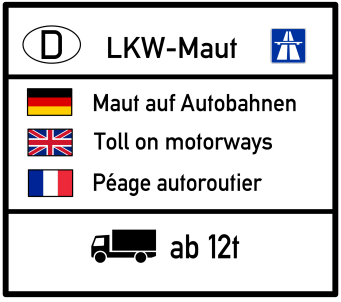


Figure: Map of the problematique (Muse 2006), signs until 2015, from `https://commons.wikimedia.org`

The German Toll System for Trucks ($> 7.5t$)

Some Numbers

- $\geq 50.000km$ federal highway
- ≥ 3500 terminals in Germany for manual booking
- ≥ 900 gantries & pillars for automatic control
- ≥ 500 inspectors for mobile (and stationary) control

Two types of users

Figure: On-Board-Units (left) based on GPS & manual booking at terminals (right). Source: BAG & TC

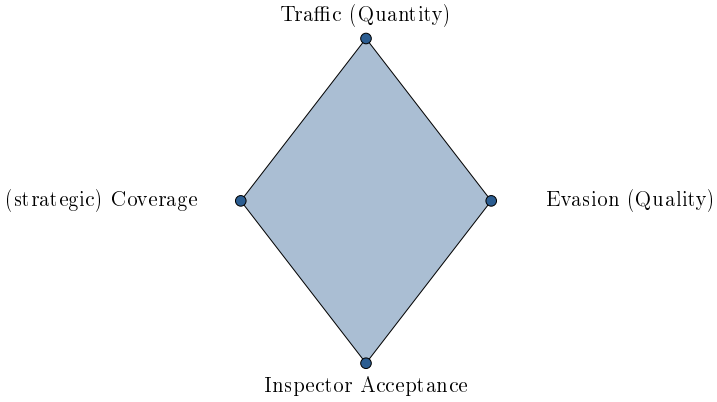
Two types of control resources

Figure: Static automatic (gantries, pillars) and flexible manual (mobile) controls of inspector teams.

Mobile Control

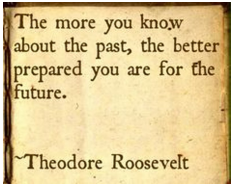
Figure: BAG team controls while overtaking. Source: BMVBS, Bundesbildstelle, BAG

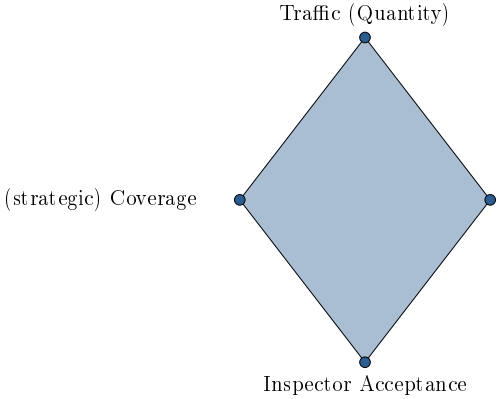
Get the balance right (DepecheMode[1983])



Get the balance right (DepecheMode[1983])

Where and when was the most traffic?



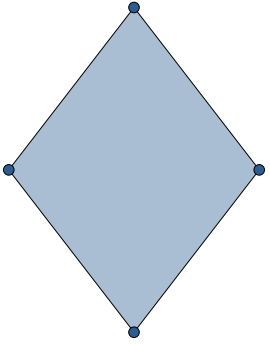


Where and when were the most evasions?

Get the balance right (DepecheMode[1983])

Where and when was the most traffic?

Traffic (Quantity)



(strategic) Coverage

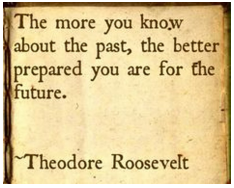
Where and when will be an incentive to evade?

Evasion (Quality)

Where and when were the most evasions?

Inspector Acceptance

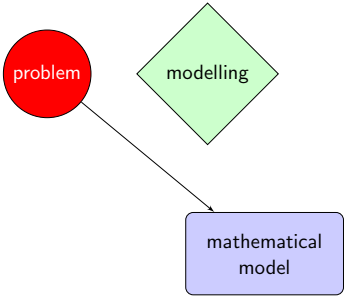
Will the optimized plan be operated?



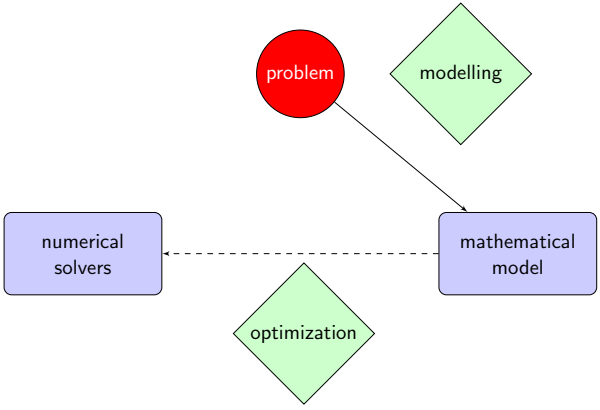
1. Who?
2. What & Why?
3. How?

Application Driven Approach - Problem Cycle

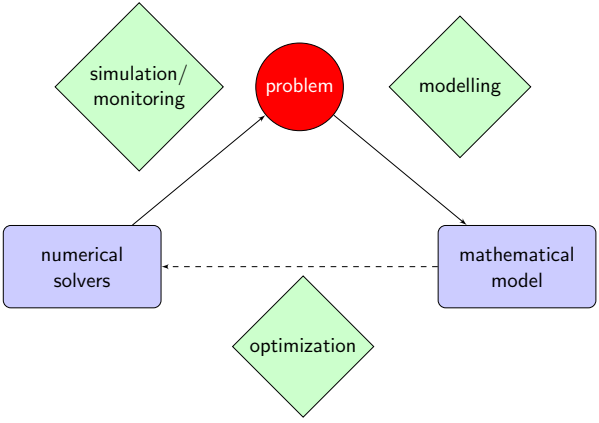
Application Driven Approach - Problem Cycle



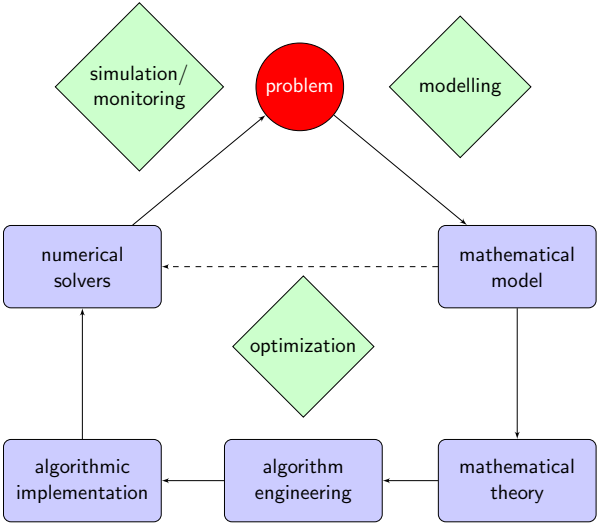
Application Driven Approach - Problem Cycle



Application Driven Approach - Problem Cycle



Application Driven Approach - Problem Cycle

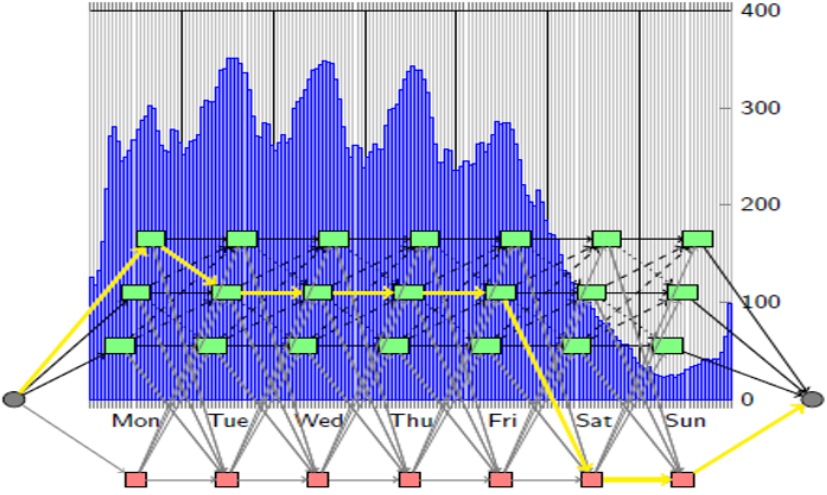


Toll Enforcement Problem

Input

- network & traffic prognosis
- vehicles and inspectors (availabilities & vacation)
- duty and rostering rules

Traffic Prognosis & Duty Graph



Duty & Roster Rules

Duty Construction Rules

- different starting and working times
- valid combinations of depots and sections
- inspector availabilities (days & times)

Roster Construction Rules & Objectives

- minimum rest time between duties
- at most n days of work
- at least m days free
- respect minimal and maximal total working time
- respect maximal number late duties
- avoid different starting times
- ...

Toll Enforcement Problem

Input

- network & traffic prognosis
- vehicles and inspectors (availabilities & vacation)
- duty and rostering rules

Output

- vehicle tours for each day
- inspector duties for each day
- roster for complete month

Toll Enforcement Problem

Input

- network & traffic prognosis
- vehicles and inspectors (availabilities & vacation)
- duty and rostering rules

Output

- vehicle tours for each day
- inspector duties for each day
- roster for complete month

R. Borndörfer, Guillaume Sagnol, T.S., Elmar Swarat:

Optimal duty rostering for toll enforcement inspectors,

Annals of Operations Research volume 252 (2017)

Roster Solution

TEP - Integrated Tour and Roster Planning

(Tour Planning)

$$\sum_{d \in D_f \cap D_j} z_d \leq 1, \qquad \forall f \in F, \forall j \in J$$

$$\sum_{d \in D_s \cap D_j \cap D_i} z_d \leq 1, \qquad \forall s \in S, \forall j \in J, \forall i \in T$$

$$\sum_{d \in D_s} \beta_{ds} z_d \geq \kappa_s, \qquad \forall s \in S$$

$$z_d \in \{0,1\}, \forall d \in D$$

TEP - Integrated Tour and Roster Planning

(Tour Planning)

$$\sum_{d \in D_f \cap D_j} z_d \leq 1, \qquad \forall f \in F, \forall j \in J$$

$$\sum_{d \in D_s \cap D_j \cap D_i} z_d \leq 1, \qquad \forall s \in S, \forall j \in J, \forall i \in T$$

$$\sum_{d \in D_s} \beta_{ds} z_d \geq \kappa_s, \qquad \forall s \in S$$

$$z_d \in \{0,1\}, \forall d \in D$$

(Roster Flow)

$$\sum_{a \in \delta^{\text{in}}(v)} x_{am} - \sum_{a \in \delta^{\text{out}}(v)} x_{am} = 0, \qquad \forall m \in M, \forall d \in D$$

$$\sum_{a \in A} b_{ar} x_{am} \leq u_{rm}, \qquad \forall m \in M, \forall r \in R$$

$$\sum_{a \in I} x_{am} \leq |I| - 1, \quad \forall I \in \mathcal{I}, \forall m \in M$$

$$x_{am} \in \{0,1\}, \quad \forall a \in A, \forall m \in M$$

TEP - Integrated Tour and Roster Planning

(Tour Planning)

$$\sum_{d \in D_f \cap D_j} z_d \leq 1, \qquad \forall f \in F, \forall j \in J$$

$$\sum_{d \in D_s \cap D_j \cap D_i} z_d \leq 1, \qquad \forall s \in S, \forall j \in J, \forall i \in T$$

$$\sum_{d \in D_s} \beta_{ds} z_d \geq \kappa_s, \qquad \forall s \in S$$

$$z_d \in \{0,1\}, \forall d \in D$$

(Roster Flow)

$$\sum_{a \in \delta^{\text{in}}(v)} x_{am} - \sum_{a \in \delta^{\text{out}}(v)} x_{am} = 0, \qquad \forall m \in M, \forall d \in D$$

$$\sum_{a \in A} b_{ar} x_{am} \leq u_{rm}, \qquad \forall m \in M, \forall r \in R$$

$$\sum_{a \in I} x_{am} \leq |I| - 1, \quad \forall I \in \mathcal{I}, \forall m \in M$$

$$x_{am} \in \{0,1\}, \quad \forall a \in A, \forall m \in M$$

(Coupling Constraints)

$$n_d z_d - \sum_{m \in M} \sum_{a \in \delta^{\text{in}}(d) \in A} x_{am} = 0, \forall d \in D$$

TEP - Integrated Tour and Roster Planning

(Objective)

$$\max \sum_{d \in D} w_d z_d - \sum_{m \in M} \sum_{a \in A} c_{am} x_{am}$$

(Tour Planning)

$$\sum_{d \in D_f \cap D_j} z_d \leq 1, \qquad \forall f \in F, \forall j \in J$$

$$\sum_{d \in D_s \cap D_j \cap D_i} z_d \leq 1, \qquad \forall s \in S, \forall j \in J, \forall i \in T$$

$$\sum_{d \in D_s} \beta_{ds} z_d \geq \kappa_s, \qquad \forall s \in S$$

$$z_d \in \{0,1\}, \forall d \in D$$

(Roster Flow)

$$\sum_{a \in \delta^{\text{in}}(v)} x_{am} - \sum_{a \in \delta^{\text{out}}(v)} x_{am} = 0, \qquad \forall m \in M, \forall d \in D$$

$$\sum_{a \in A} b_{ar} x_{am} \leq u_{rm}, \qquad \forall m \in M, \forall r \in R$$

$$\sum_{a \in I} x_{am} \leq |I| - 1, \quad \forall I \in \mathcal{I}, \forall m \in M$$

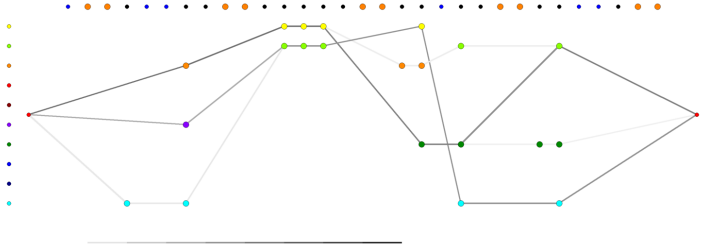
$$x_{am} \in \{0,1\}, \quad \forall a \in A, \forall m \in M$$

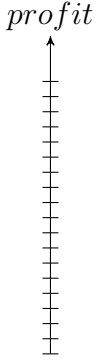
(Coupling Constraints)

$$n_d z_d - \sum_{m \in M} \sum_{a \in \delta^{\text{in}}(d) \in A} x_{am} = 0, \forall d \in D$$

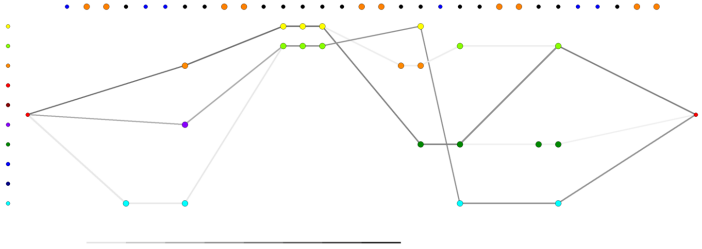
Solution Approach in a Nutshell

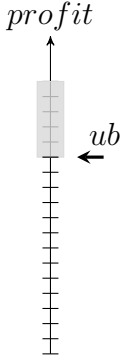
Solution Approach in a Nutshell



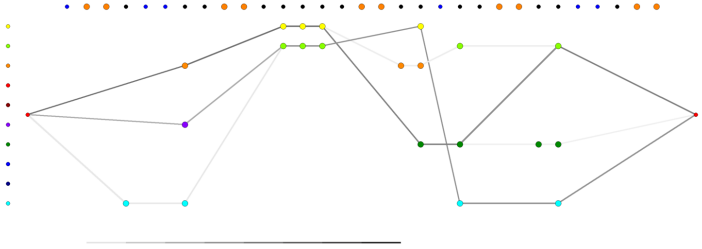


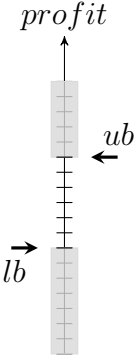
Solution Approach in a Nutshell



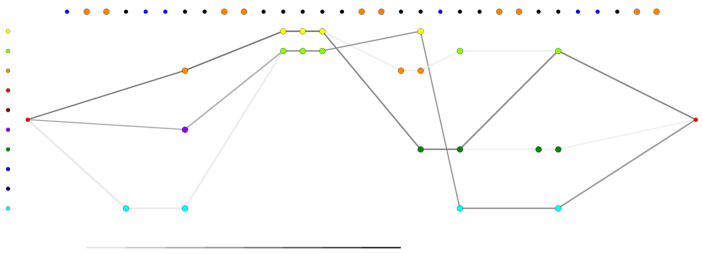


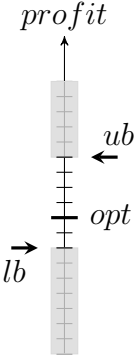
Solution Approach in a Nutshell





Solution Approach in a Nutshell





Performance Boosters - Buzzwords only

Primal Side - Generate Solutions

- DEX (Lin-Kernighan heuristic)
- Coarse-To-Fine column generation heuristic

Dual Side - Improve LP Bound

- strong coupling constraints
- integer rounding for binary knapsacks

The Deployment

Research Stage 2010-2013

- model development
- prototype software
- standard model

The Deployment

Research Stage 2010-2013

- model development
- prototype software
- standard model

Deployment Stage 2013-2014

- start with 2 regions
- successive rollout in Germany (> 20 regions)
- special cases & more features & more data

The Deployment

Research Stage 2010-2013

- model development
- prototype software
- standard model

Deployment Stage 2013-2014

- start with 2 regions
- successive rollout in Germany (> 20 regions)
- special cases & more features & more data

since then in production

- more than $5 * 12 * 24 > 1400$ **MIP**ed schedules

Key Feature I: Import Reference Solution

Reference Solution

Map any available technical solution to your model solution (hard) or adapt the objective function such that most is reproduced (soft).

Key Feature I: Import Reference Solution

Reference Solution

Map any available technical solution to your model solution (hard) or adapt the objective function such that most is reproduced (soft).

- discover untold degrees of freedom `(vars)`

Key Feature I: Import Reference Solution

Reference Solution

Map any available technical solution to your model solution (hard) or adapt the objective function such that most is reproduced (soft).

- discover untold degrees of freedom `(vars)`
- discover hidden relaxations of the rules `(cons)`

Key Feature I: Import Reference Solution

Reference Solution

Map any available technical solution to your model solution (hard) or adapt the objective function such that most is reproduced (soft).

- discover untold degrees of freedom `(vars)`
- discover hidden relaxations of the rules `(cons)`
- discover desired properties of the solution `(obj)`

Key Feature II: Fairness in Rostering

The game of buck passing

Some inspectors have temporal restrictions such that other inspectors have a higher probability to get critical duties.

Key Feature II: Fairness in Rostering

The game of buck passing

Some inspectors have temporal restrictions such that other inspectors have a higher probability to get critical duties.

- consider preferences of inspectors

Key Feature II: Fairness in Rostering

The game of buck passing

Some inspectors have temporal restrictions such that other inspectors have a higher probability to get critical duties.

- consider preferences of inspectors
- two stage optimization approach

Key Feature II: Fairness in Rostering

The game of buck passing

Some inspectors have temporal restrictions such that other inspectors have a higher probability to get critical duties.

- consider preferences of inspectors
- two stage optimization approach
  1. `X = solveModel(M, considerRestrictions = false )`

Key Feature II: Fairness in Rostering

The game of buck passing

Some inspectors have temporal restrictions such that other inspectors have a higher probability to get critical duties.

- consider preferences of inspectors
- two stage optimization approach
  1. `X = solveModel(M, considerRestrictions = false )`
  2. `M = fixDutiesNotViolatingRestrictions( X )`

Key Feature II: Fairness in Rostering

The game of buck passing

Some inspectors have temporal restrictions such that other inspectors have a higher probability to get critical duties.

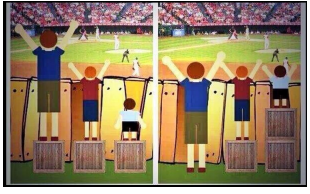
- consider preferences of inspectors
- two stage optimization approach
  1. `X = solveModel(M, considerRestrictions = false )`
  2. `M = fixDutiesNotViolatingRestrictions( X )`
  3. `solveModel(M, considerRestrictions = true )`

Key Feature II: Fairness in Rostering

The game of buck passing

Some inspectors have temporal restrictions such that other inspectors have a higher probability to get critical duties.

- consider preferences of inspectors
- two stage optimization approach
  1. `X = solveModel(M, considerRestrictions = false )`
  2. `M = fixDutiesNotViolatingRestrictions( X )`
  3. `solveModel(M, considerRestrictions = true )`



Lessons learned

Keys to successful deployment

- Find a common language

Lessons learned

Keys to successful deployment

- Find a common language
-
- Imagine you are $p, \forall p \in$ `PLAYERS`

Lessons learned

Keys to successful deployment

- Concentrate on standardization
- Find a common language
-
- Imagine you are $p, \forall p \in$ `PLAYERS`

Lessons learned

Keys to successful deployment

- Build a powerful flexible mathematical model (MIP)
- Concentrate on standardization

- Find a common language
-
- Imagine you are $p, \forall p \in$ `PLAYERS`

Lessons learned

Keys to successful deployment

- Build a powerful flexible mathematical model (MIP)
- Concentrate on standardization

- Enter quickly and stay in the feedback loop
- Find a common language
-
- Imagine you are $p, \forall p \in$ `PLAYERS`

Lessons learned

Keys to successful deployment

- Accept moving targets and new wishes on the journey
- Build a powerful flexible mathematical model (MIP)
- Concentrate on standardization

- Enter quickly and stay in the feedback loop
- Find a common language
-
- Imagine you are $p, \forall p \in \texttt{PLAYERS}$

Lessons learned

Keys to successful deployment

- Accept moving targets and new wishes on the journey
- Build a powerful flexible mathematical model (MIP)
- Concentrate on standardization
- Do tackle details & special cases
- Enter quickly and stay in the feedback loop
- Find a common language
-
- Imagine you are $p, \forall p \in \texttt{PLAYERS}$

Lessons learned

Keys to successful deployment

- Accept moving targets and new wishes on the journey
- Build a powerful flexible mathematical model (MIP)
- Concentrate on standardization
- Do tackle details & special cases
- Enter quickly and stay in the feedback loop
- Find a common language
-
- Imagine you are $p, \forall p \in$ `PLAYERS`
- Use your own tools!

Because I like to practice what I preach [Strangelove, DeMo 1987])

Thanks for your Attention & Patience!