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Introducing Interdepedent Simple Temporal Networks under Uncertainty for Multi-agent Temporal Planning

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PICS – LGP – UTTOP – Tarbes

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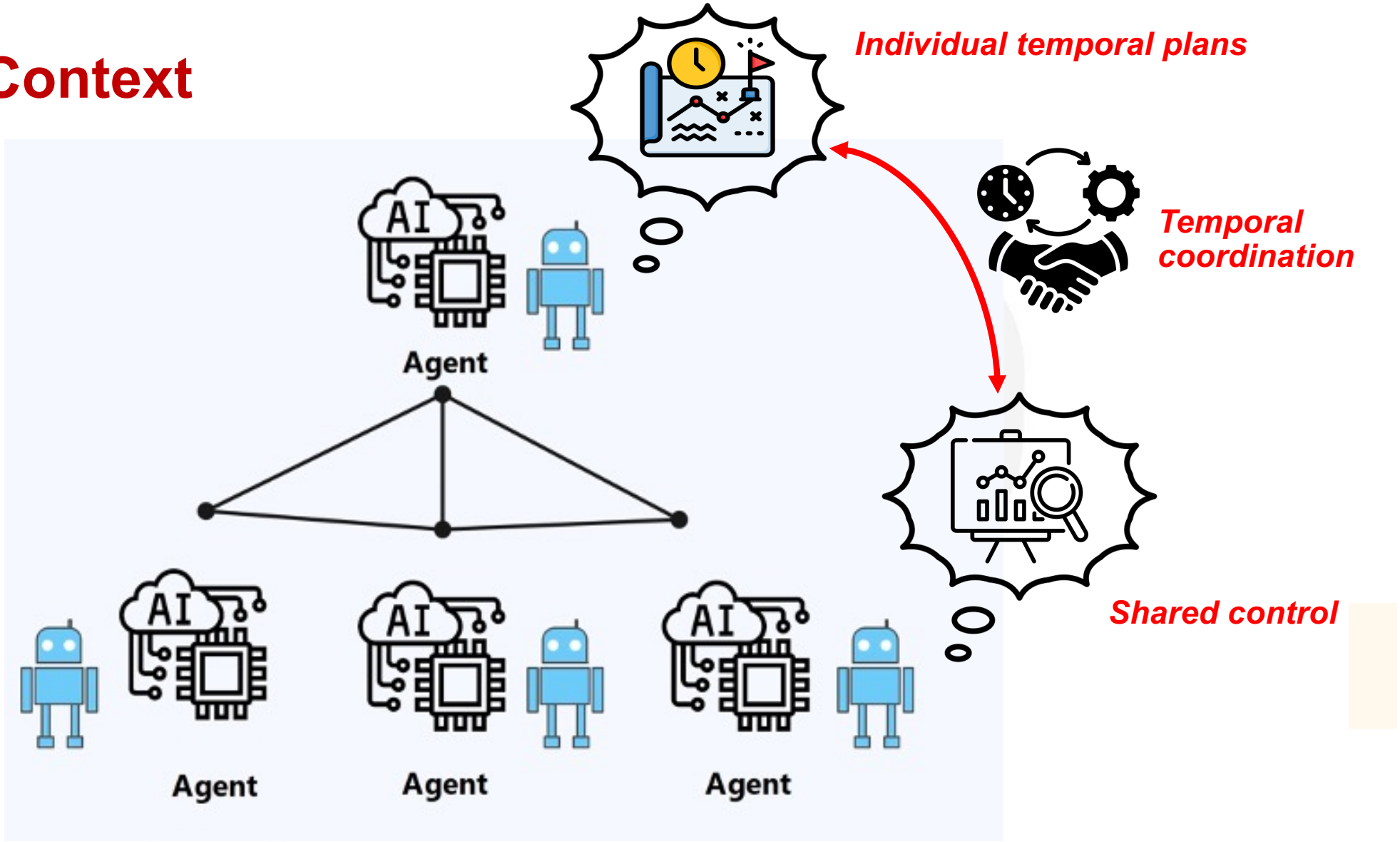
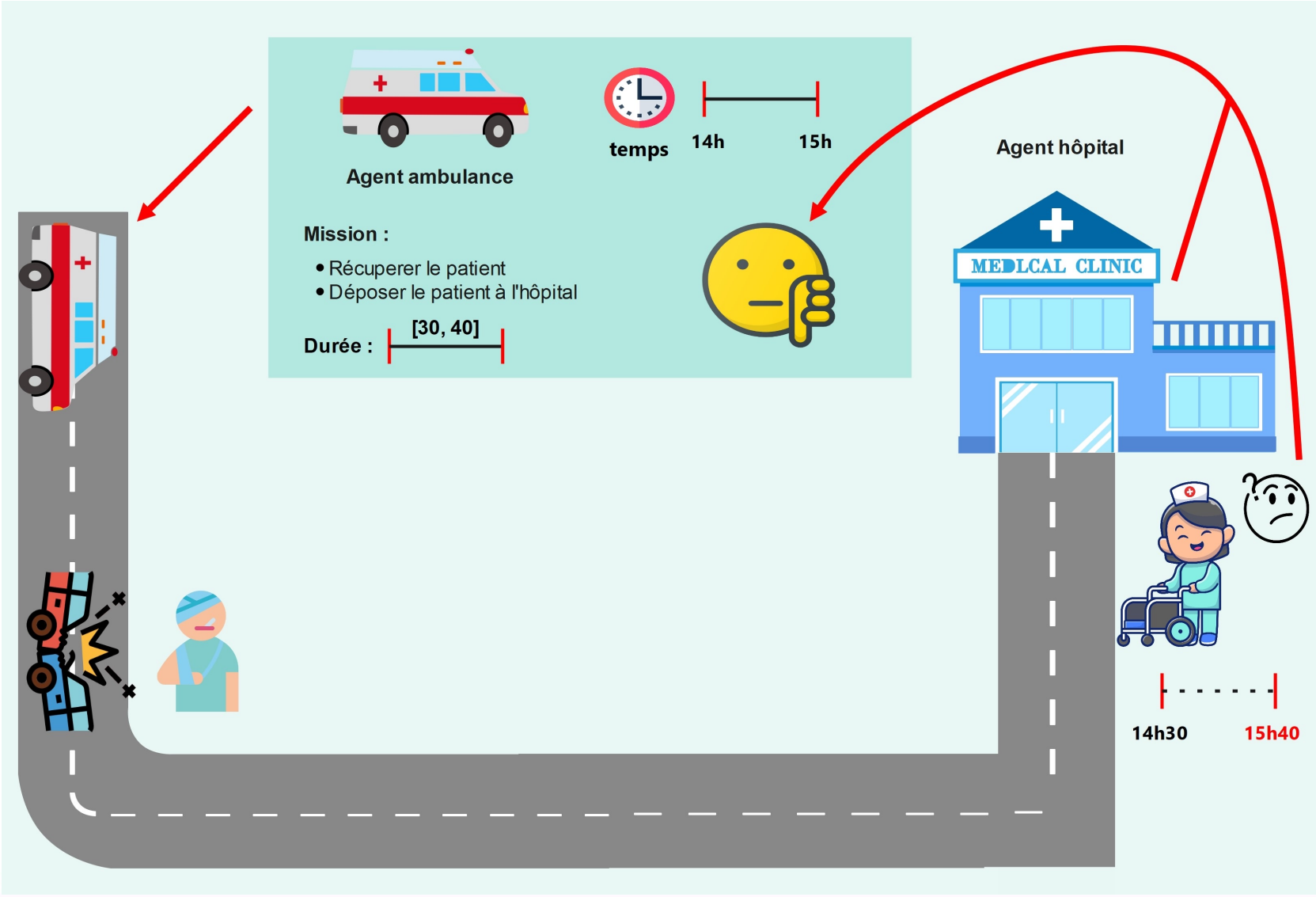
Context and Motivation

Context

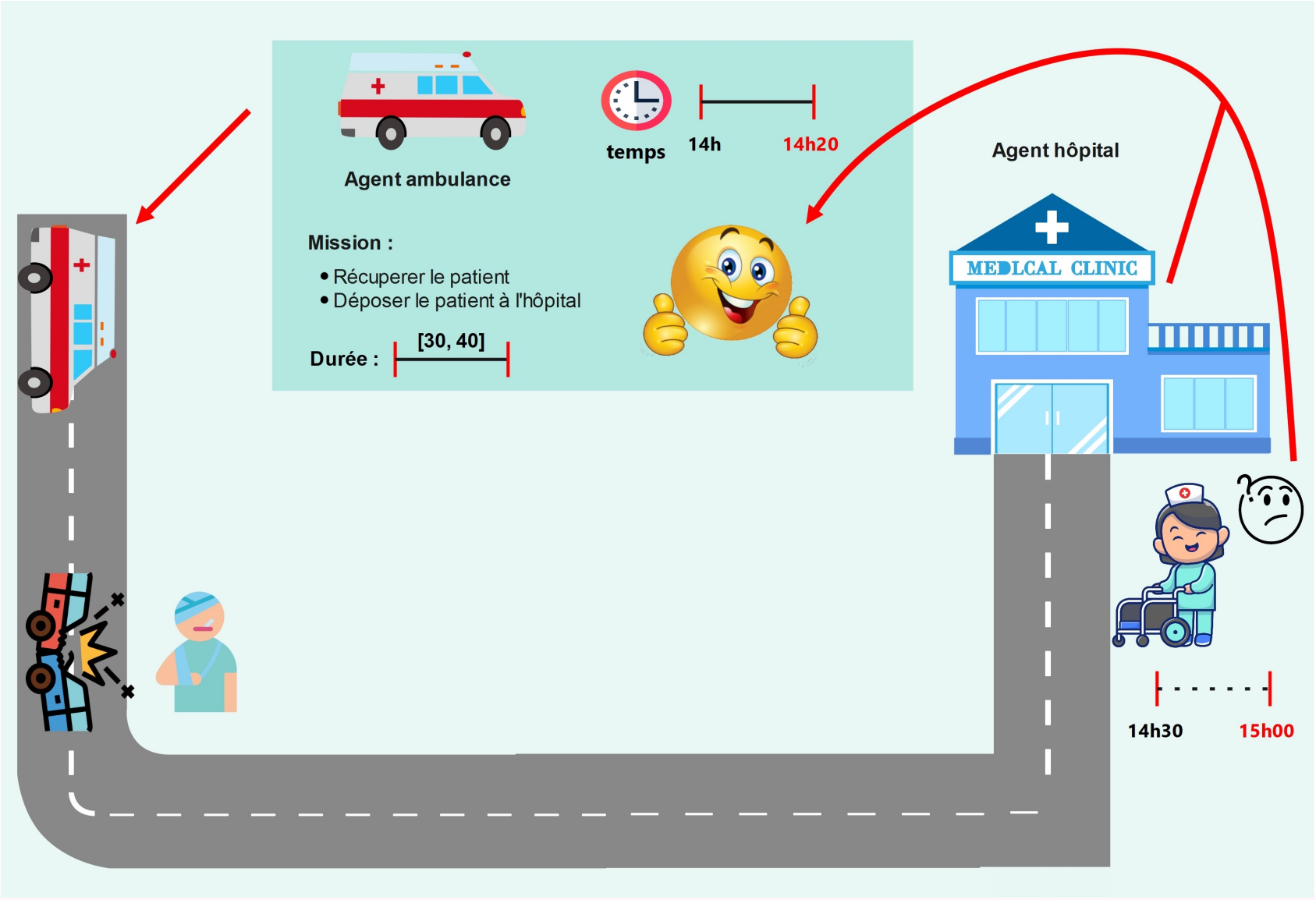


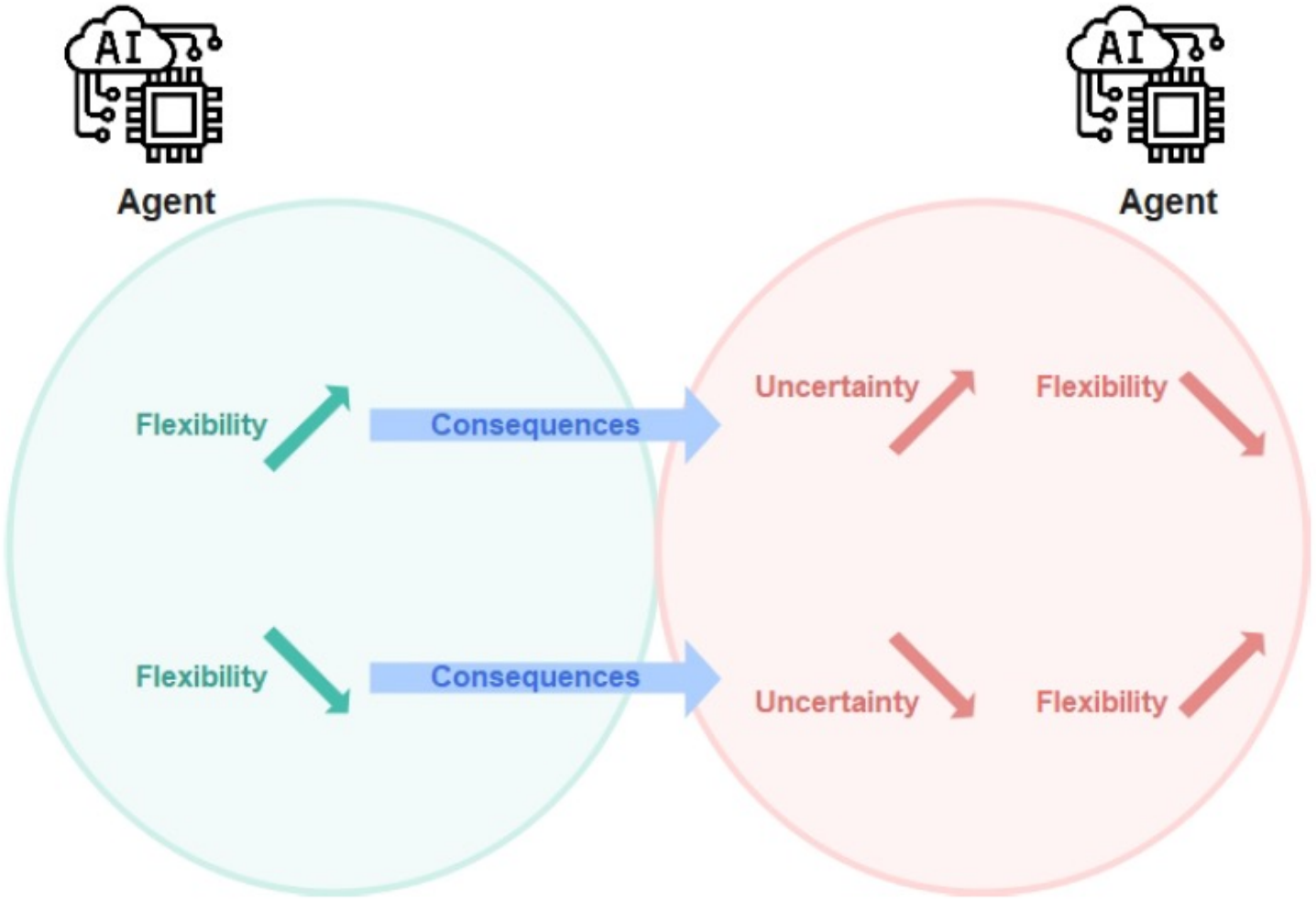
Homogeneous agents

Illustrative example



Illustrative example



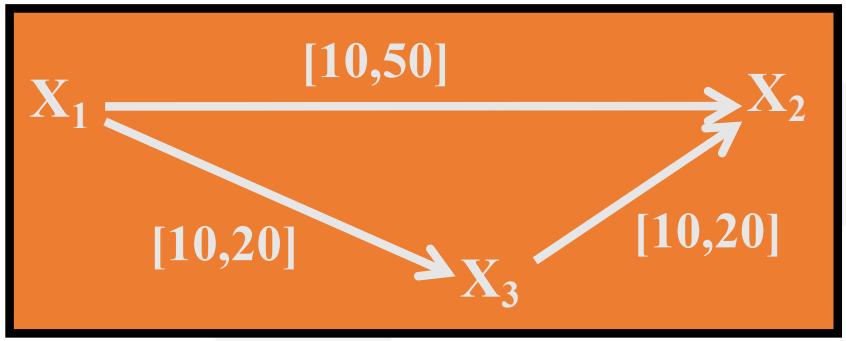

AI
Agent
AI
Agent
Flexibility
Consequences
Uncertainty
Flexibility
Flexibility
Consequences
Uncertainty
Flexibility

Background

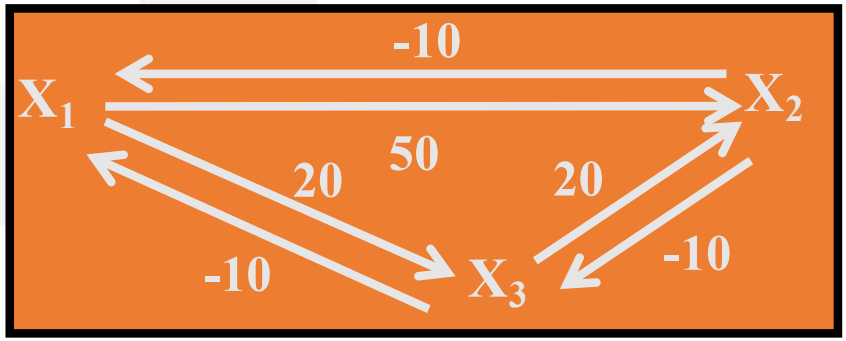
STN

STN (Simple Temporal Network) **is consistent** if there exists an assignment of the time-points that satisfies all the constraints

STN = (V, E)



Distance graph



Polynomial propagation type algorithm in $O(n^3)$:

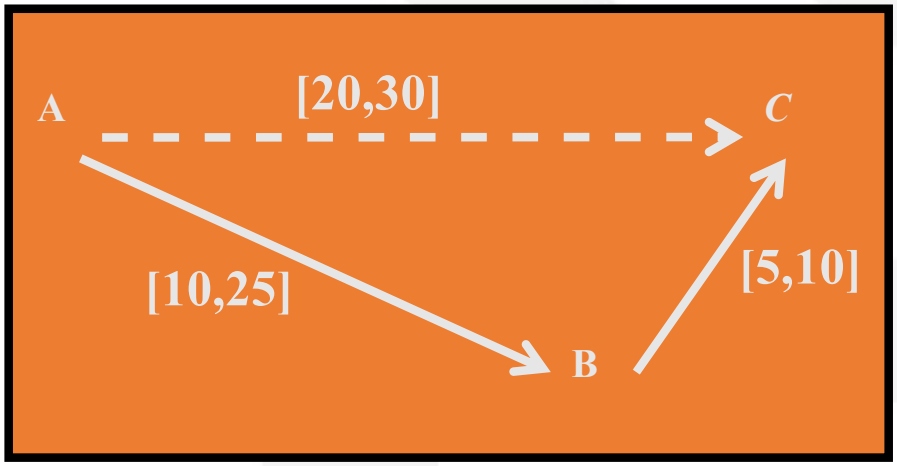
- Path consistency
- Floyd-Warshall

Negative cycle = inconsistency

STNU

STNU (Simple Temporal Network with Uncertainty) *[Vidal et Fargier, 1999]*

- idem STN + = intervals of possible durations : **controllable** / **contingent**



STNU X = (V, E, C)

Consistency →→→ **Controllability :**

A *situation* $\omega = \langle \omega_1 \in [L_1, U_1], \ldots, \omega_C \in [L_{|C|}, U_{|C|}] \rangle \in \Omega$

A *schedule* $\delta = \{\delta(v_1), \ldots, \delta(v_{|V_c|})\}$ *with* $\forall i, v_i \in V_c$

Clbty ≡ There exists a valid ∂ for each ω ?

3 levels of Controllability

Definition 7. *(**Strong Controllability (SC)**) An STNU $\mathcal{X}$ is **strongly controllable** iff $\exists\, \delta$ such that $\forall \omega \in \Omega$, δ is a solution of $\mathcal{X}_\omega$.*
Execution semantics: $\forall v_i \in V_c$, $dec(v_i) = v_0$, and the observations are free: possibly no observation ($\forall \omega_k \in \omega$, $obs(\omega_k) = \varnothing$) or observations during execution that will just update the bounds of the constraints in the network.

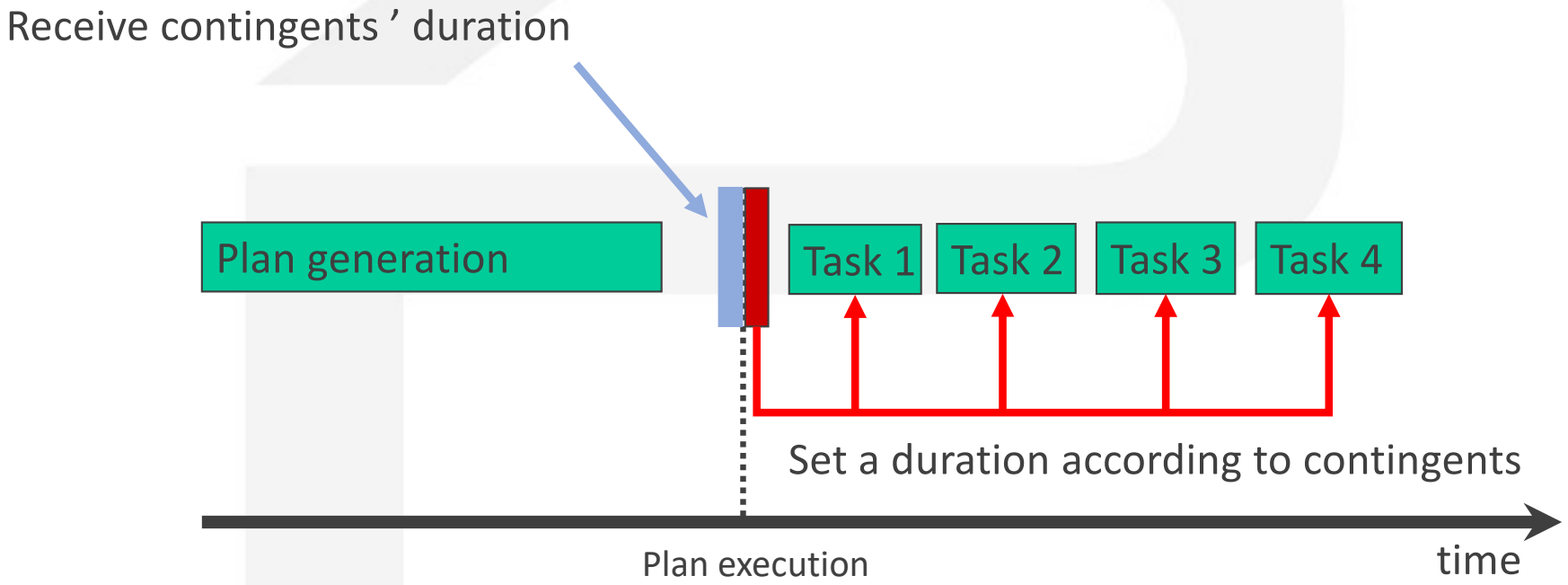
Definition 6. *(**Dynamic Controllability (DC)**) An STNU $\mathcal{X}$ is **dynamically controllable** iff it is weakly controllable and $\forall v_i \in V_c, \forall \omega, \omega' \in \Omega$, $\omega^{\leq v_i} = \omega'^{\leq v_i} \implies \delta(v_i) = \delta'(v_i)$*
Execution semantics: $\forall \omega_k \in \omega$, $obs(\omega_k)=end(c_k)$, and $\forall v_i \in V_c$, $dec(v_i) = v_i$

Definition 5. *(**Weak Controllability (WC)**) An STNU $\mathcal{X}$ is **weakly controllable** iff $\forall \omega \in \Omega, \exists \delta$ such that δ is a solution of $\mathcal{X}_\omega$.*
Execution semantics: $\forall \omega_k \in \omega$, $obs(\omega_k)=v_0$, and the decision policy is free: $\forall v_i \in V_c$, $dec(v_i) \preceq v_i$

Strong Controllability $\implies$ Dynamic Controllability $\implies$ Weak Controllability

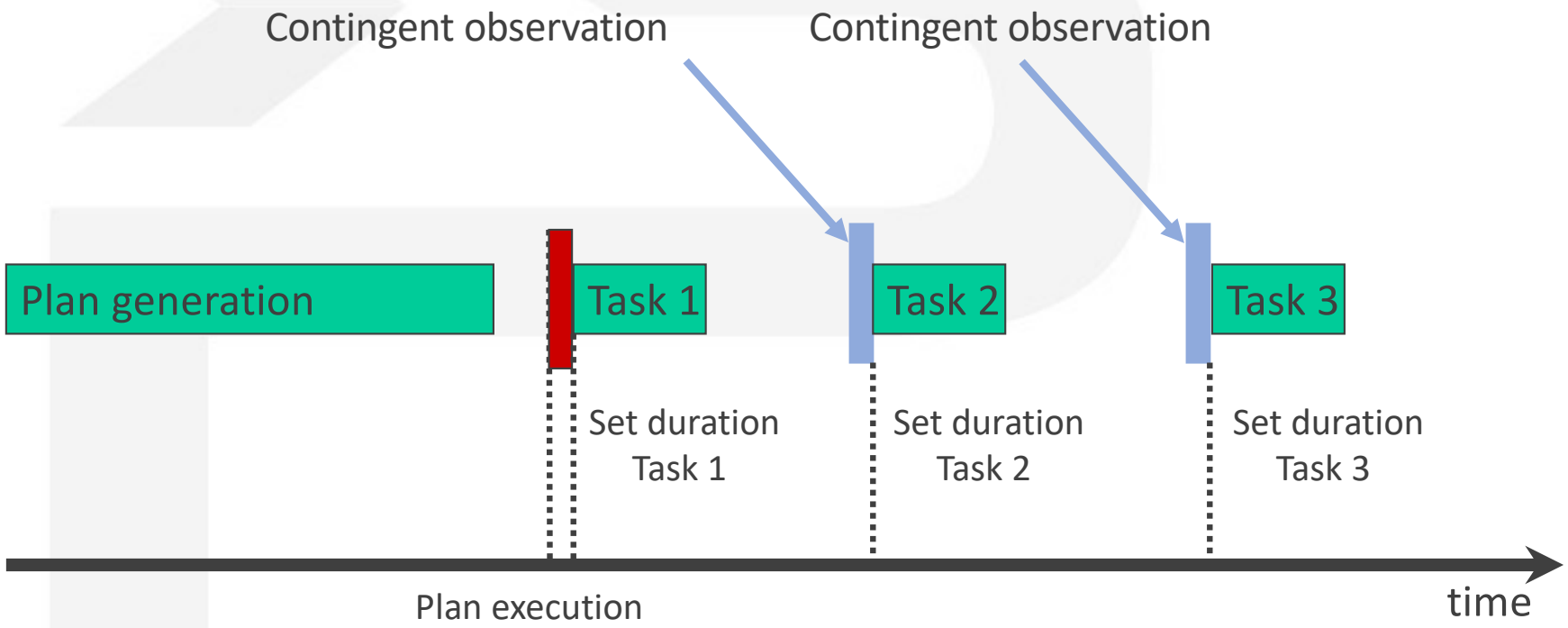
WC

- **Weak Controllability (WC):** assumes contingent durations will be known just before execution = pick up the solution that matches it.



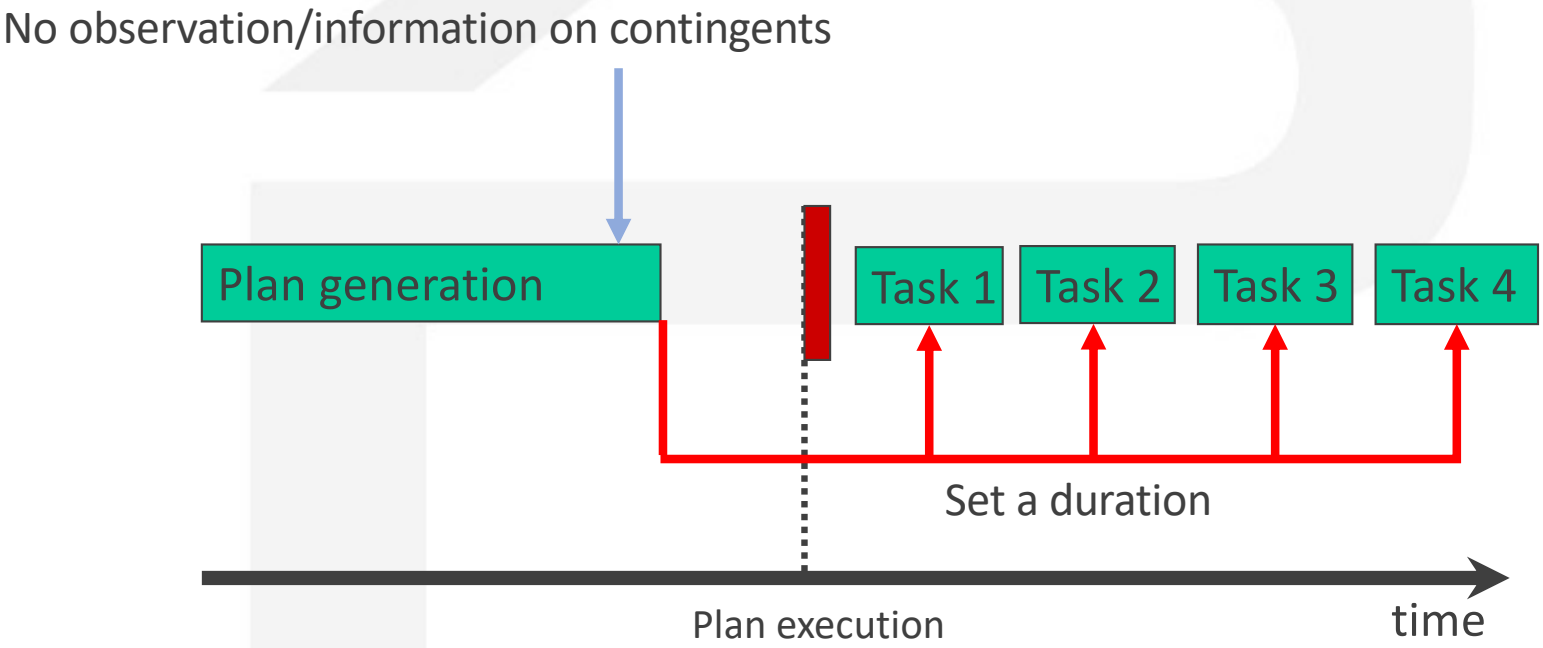
DC

- **Dynamic Controllability (SC):** assumes sequential decisions adapt to past observations.



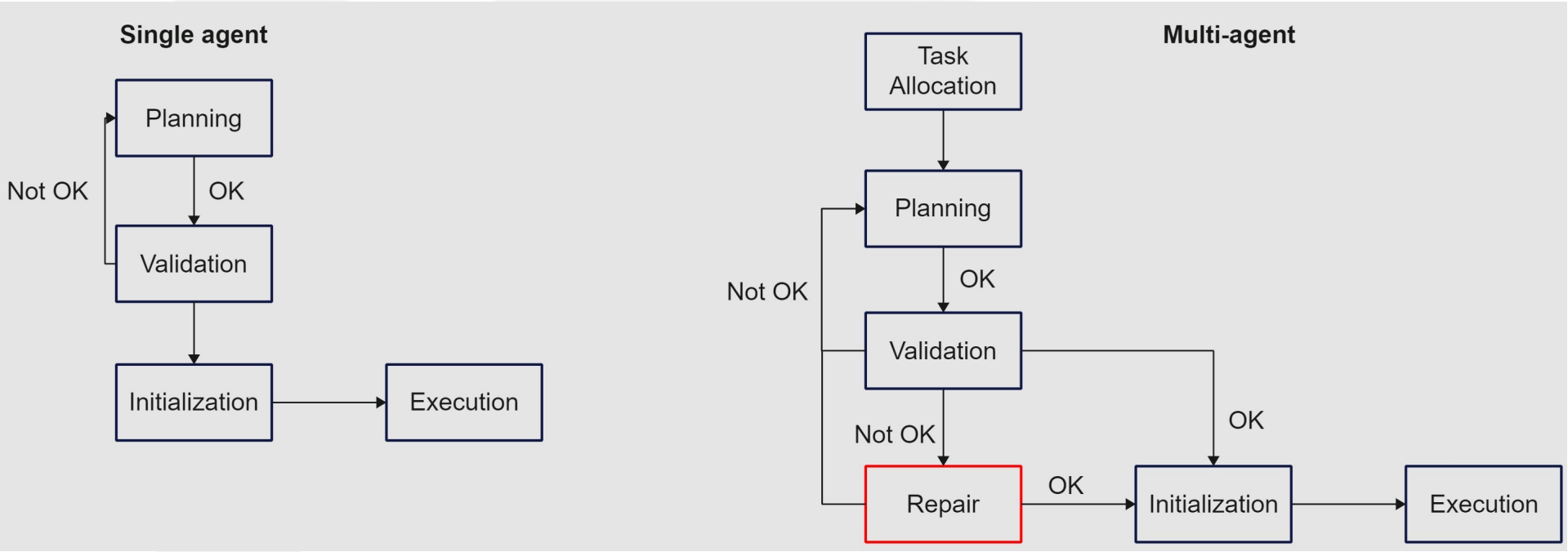
SC

- **Strong Controllability:** assumes no observations, which requires a fixed schedule that satisfies the constraint, whatever the contingent durations will be.



A new multi-agent architecture + repair needs

- Uncertainties come from other agents



- Repair an agent plan by adjusting uncertain durations (local repair)

Global model for the multi-agent temporal coordination ?

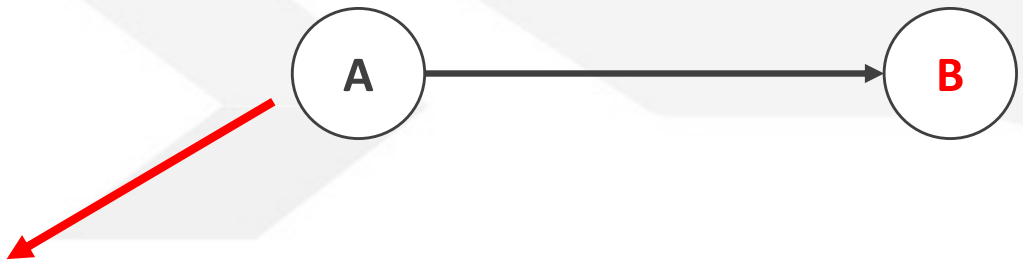
Question ?

How to model the problem ?

Is there a model in the literature for that ?

→ No !

Model: the notion of contracts

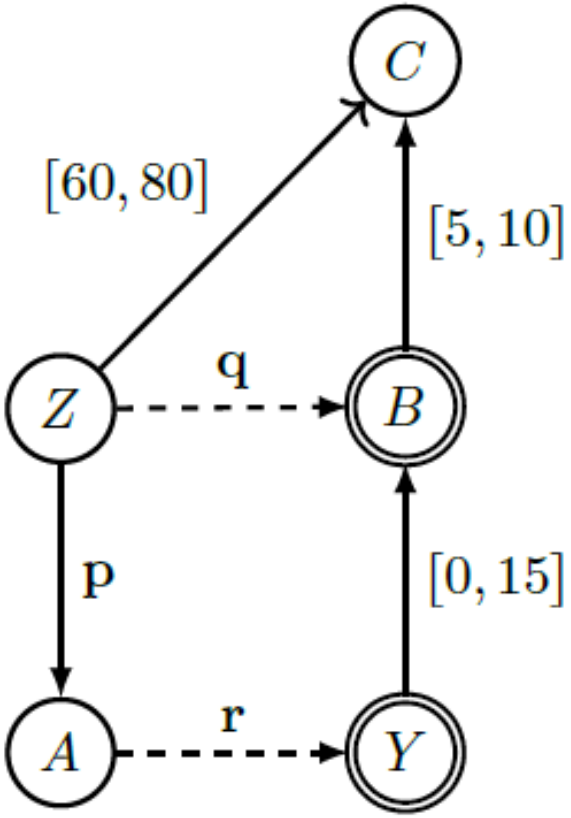


A contract:

- A common constraint between at least 2 agents
- Only one **owner** agent that will decide **B**
- May have multiple **compliant** agents that observes **B**

Model: contracting STNU

From STNU to cSTNU



Contracts:

- p (owned)
- q and r (observed)

Label	Contract
p	[20, 25]
q	[60, 75]
r	[25, 35]

outside the cSTNU

Model: MISTNU

Multi-agent Interdependent Simple Temporal Network under Uncertainty (MISTNU)

Definition 9. *(MISTNU) A MISTNU is a tuple* $\mathcal{G} = \langle A, \Sigma, B \rangle$ *such that:*

- A *is a set of agents* $\{a_1, a_2, \ldots, a_n\}$;
- Σ *is a set of cSTNUs* $\mathcal{S}_a = \langle V_a, R_a, W_a, E_a, C_a, O_a \rangle$, *one for each* $a \in A$, *such that*
  - $\forall a \in A$, $v_z \in V_a$, *where* v_z *is the mutual reference time point;*
  - *for every pair of agents* $a, b \in A$, $W_a \cap W_b = \varnothing$
- B *is a map from contracts to bounds* $B : \bigcup_{a \in A}(R_a \cup W_a) \rightarrow \mathbb{R}^2$. *For the sake of this paper, we write* l *and* u *for* $\langle l_p, u_p \rangle = B(p)$.

Model: MISTNU

Multi-agent Interdependent Simple Temporal Network under Uncertainty (MISTNU)

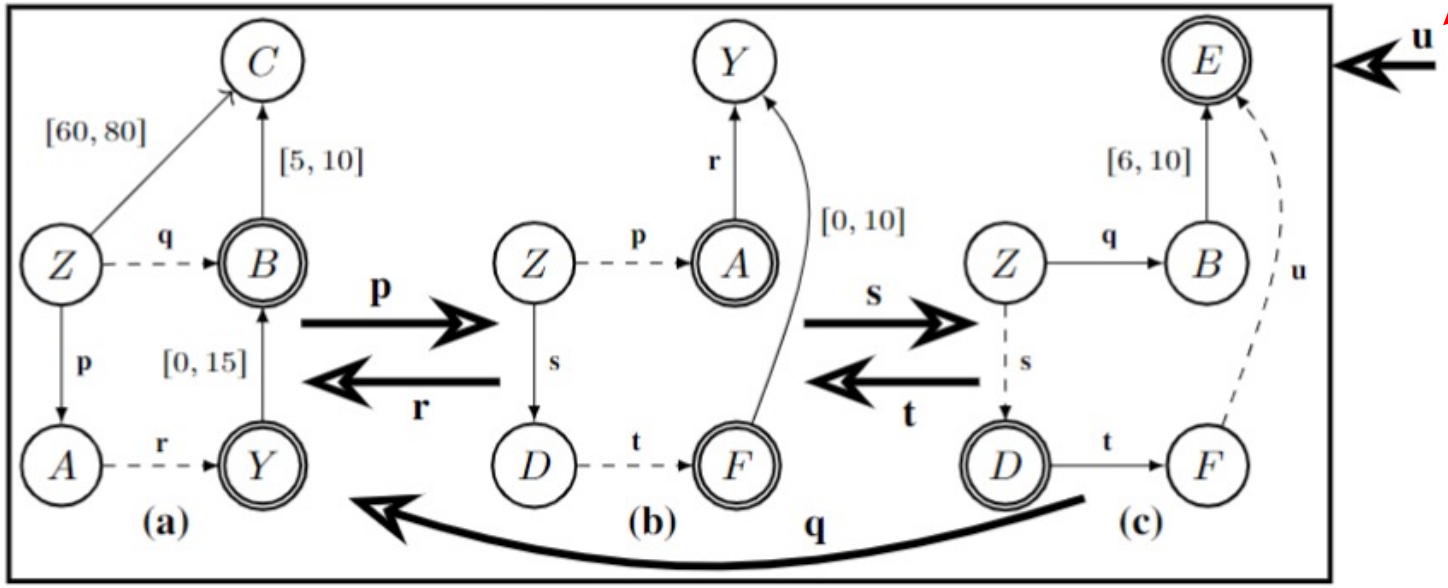
Expressivity of MISTNU:

- Represent each agent and their networks with contracts
- Still represent real contingents (contract with no owner)
- Only 1 agent = STNU

→ **Extend existing multi-agent models**

Model: MISTNU example

From external agent



Label	Contract
p	[20, 25]
q	[60, 75]
r	[25, 35]
s	[30, 35]
t	[15, 25]
u	[15, 20]

Model: MISTNU properties

▸ **Definition 10.** ***(cSTNU reduction)*** *Given a cSTNU* $\mathcal{S} = \langle V, R, W, E, C, O \rangle$ *and a map* $B : W \cup R \to \mathbb{R}^2$ *giving bounds to contracts,* $\mathcal{S}$ *can be reduced to an STNU* $S^{\mathcal{G}} \doteq \langle V, E', C' \rangle$ *with:*

- $E' = E \cup \{v_i \xrightarrow{[l,u]} v_j \mid v_i \xrightarrow{p} v_j \in O,\ B(p) = \langle l, u \rangle\}$
- $C' = \{v_i \dashrightarrow^{[l,u]} v_j \mid v_i \dashrightarrow^{p} v_j \in C \cup O,\ B(p) = \langle l, u \rangle\}$

Model: MISTNU properties

▸ **Definition 15.** *(**Controllability**) Given a MISTNU* $\mathcal{G} = \langle A, \Sigma, B \rangle$*, we define the* τ***-controllability*** L_τ *of* $\mathcal{G}$ *with* $\tau = \{Weak, Dynamic, Strong\}$ *as:*

$$L_\tau \equiv \forall S_a \in \Sigma, S_a^{\mathcal{G}} \text{ is } \tau - controllable.$$

where $S_a^{\mathcal{G}}$ *is the STNU obtained from* S_a *by the cSTNU reduction of Definition 11.*

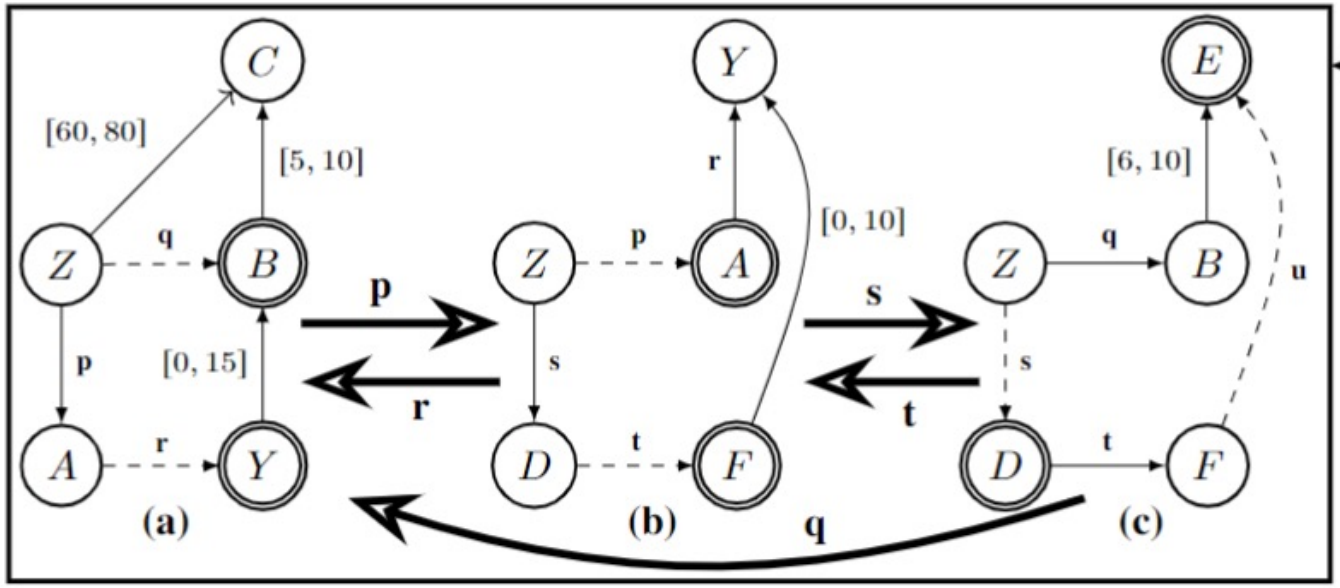
Model: MISTNU repair

How to define the repair problem ?

▸ **Definition 16.** *(**Repair**) Given a global model* $\mathcal{G} = (A, \Sigma, B)$ *such that for some agent* $a \in A$, $\mathcal{S}_a$ *is not* τ*-controllable with* $\tau = \{Weak, Dynamic, Strong\}$. *The* L_τ***-repair problem*** *consists in finding new bounds* B' *for a global model* $\mathcal{G}' = (A, \Sigma, B')$ *such that:*

- $\forall p \in P$ *let* $\langle l, u \rangle = B(p)$ *and* $\langle l', u' \rangle = B'(p)$ *where* $l' \geqslant l$, $u' \leqslant u$;
- $\mathcal{G}'$ *is* L_τ*-controllable.*

Model: MISTNU example



From external agent

Label	Contract	Repair
p	[20, 25]	[21, 25]
q	[60, 75]	[65, 73]
r	[25, 35]	[33, 35]
s	[30, 35]	[31, 35]
t	[15, 25]	[15, 25]
u	[15, 20]	[15, 20]

New bounds

Model: MISTNU repair

▸ **Definition 17.** *(**Optimal Repair**) Let $\mathcal{G} = (A, \Sigma, B)$, be a non L_τ MISTNU and let $R_\mathcal{G}$ be the set of all the solutions to the L_τ-repair problem for $\mathcal{G}$. An **optimal** L_τ**-repair** for $\mathcal{G}$ is defined as:*

$$\underset{\mathcal{G}' \in R_\mathcal{G}}{\operatorname{argmin}} \left(\sum_{p \to \langle l', u' \rangle \in B'} ((l' - l) + (u - u')) \mid \langle l, u \rangle = B(p) \right)$$

Model: MISTNU repair

▸ **Definition 18.** *(**Fair-Optimal Repair**) Let $\mathcal{G} = (A, \Sigma, B)$, be a non L_τ-controllable MISTNU and let $R_{\mathcal{G}}^{opt}$ be the set of all the solutions to the optimal L_τ-repair problem for $\mathcal{G}$. A **fair-optimal L_τ-repair** for $\mathcal{G}$ is defined as:*

$$\underset{\mathcal{G}' \in R_{\mathcal{G}}^{opt}}{\operatorname{argmax}} \left(\left| \{ \langle p_1, p_2 \rangle \in C^2_{|P|} \mid \frac{((l'_{p_1} - l_{p_1}) + (u_{p_1} - u'_{p_1}))}{u_{p_1} - l_{p_1}} = \frac{((l'_{p_2} - l_{p_2}) + (u_{p_2} - u'_{p_2}))}{u_{p_2} - l_{p_2}} \} \right| \right)$$

Model: MISTNU complexity

Complexity of the checking problem

Strong and Dynamic controllability (SC/DC):

- Checking SC and DC for STNU is polynomial

→ **Polynomial !**

Weak controllability (WC):

- Checking WC is co-NP-complete for STNU

→ **Co-NP-complete**

Model: MISTNU complexity

Complexity of the repair problem

Strong and Dynamic controllability (SC/DC):

- Need to check all possible combinations of lower and upper bounds
- Checking one combination is polynomial

→ **NP-complete !**

Weak controllability (WC):

- Need to check all possible combinations of lower and upper bounds
- Checking one combination is co-NP-complete

→ **PSPACE !**

Model: MISTNU complexity

Controllability	Checking	Repair
Weak	co-NP-complete	PSPACE
Dynamic	P	NP-complete
Strong	P	NP-complete

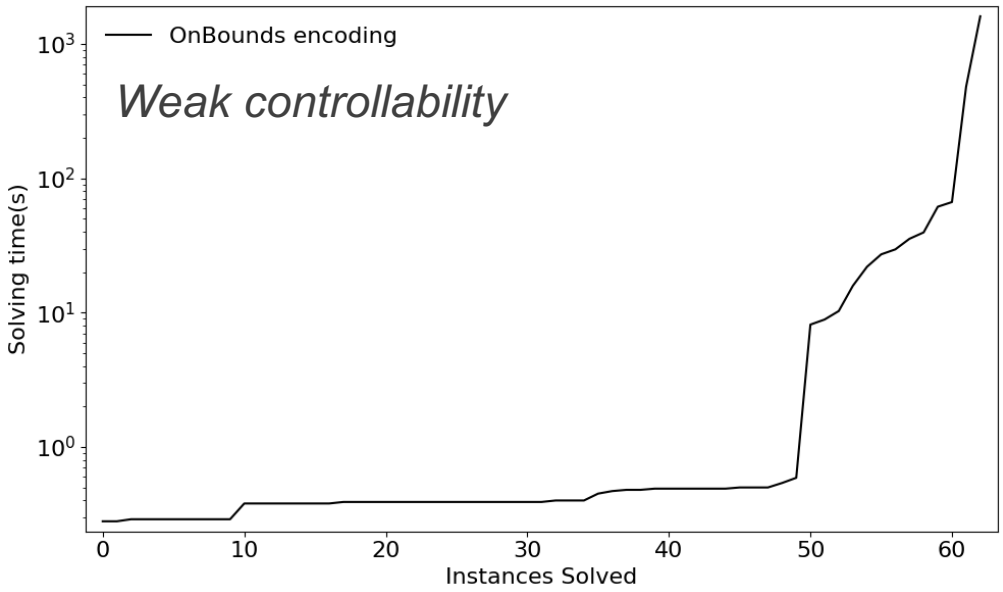
Model: MISTNU repair algorithms

algorithms for the repair problem

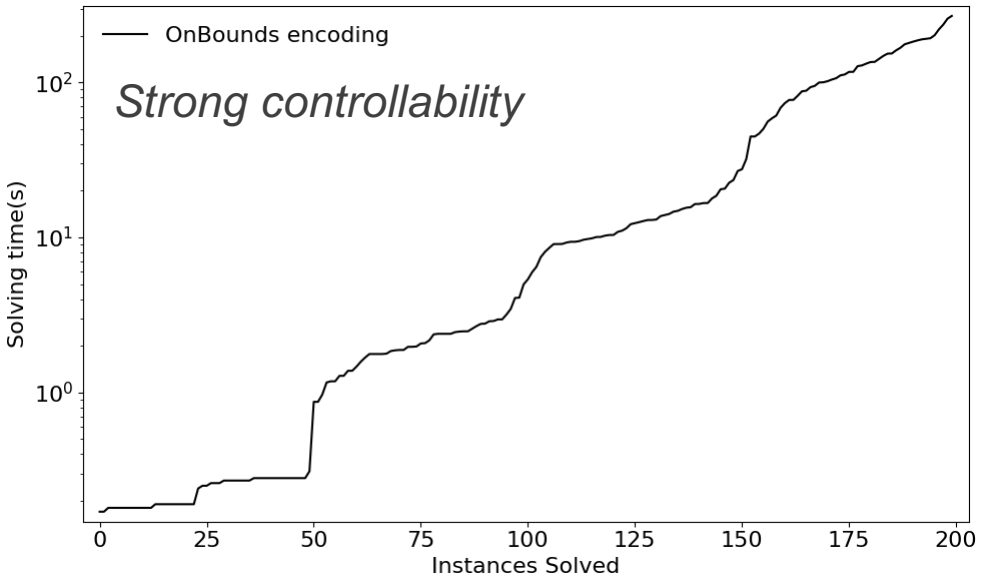
Centralized repair:

- SMT encoding for Weak and Strong controllability

400 instances **1h time limit**



400 instances **1h time limit**



Conclusion

- Introduce a novel model for multi-agent Temporal Networks that can represent the (temporal) uncertainty that comes from another agent
- We introduce a novel problem for Temporal Networks which is the repair problem
- We proposed a first approach to solve the Weak and Strong repair problem
- Such model allow to refine plans by negotiating the duration of some tasks which allow to provide more flexible plans at the planning stage

Thank you !

Time for questions