



Toward Human-Machine Cooperation

Keynote lecture

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How to integrate the Human Operator(s) into systems not-fully automated

For which classes of activities ?

- Continuous Control Tasks (vehicle driving)
- Discontinuous supervision tasks : (large production or transport systems)
 - fault detection
 - trouble shooting
 - . diagnosis/prognosis
 - . decision making
 - . recovering action
 - . following the action

-Arguments against the human integration

- Bounded human capabilities (precision, power)
- Inter and intra-individual human variations
(uncertainty of the prediction of their behaviour)

-Arguments in favour of the human integration

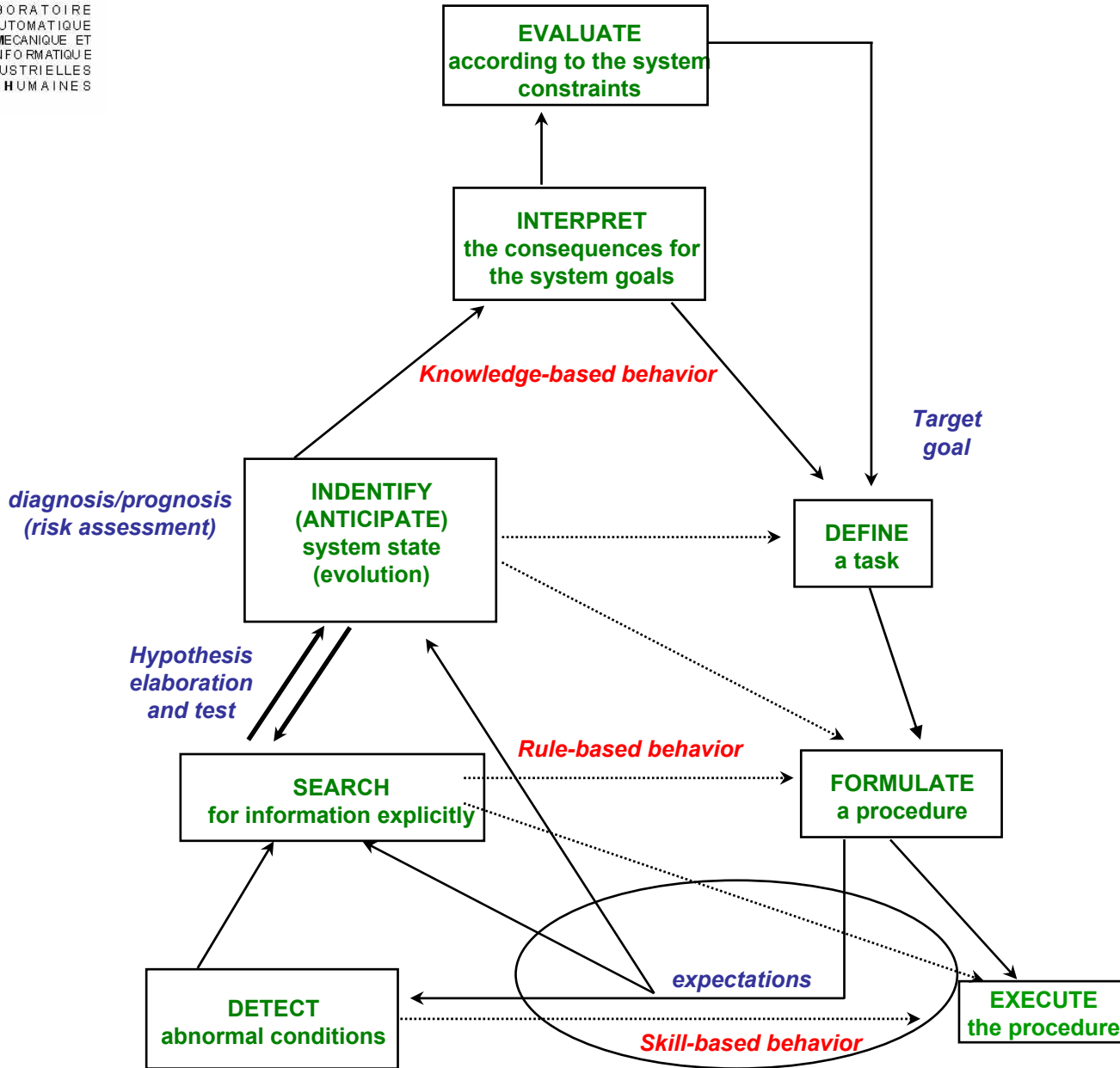
- Bounded decision capabilities of the automated systems :
 - . perception, decision making and control capabilities of the machine remain limited
 - . loss of « imagination » of the machine

-Technocentered Pathway

- Human beings are not welcome ... but needed
- Their roles are defined by default :
 - activities too complex to be automated
 - without taking the human capabilities for these activities into account
- That could result in human errors

Anthropocentered Pathway

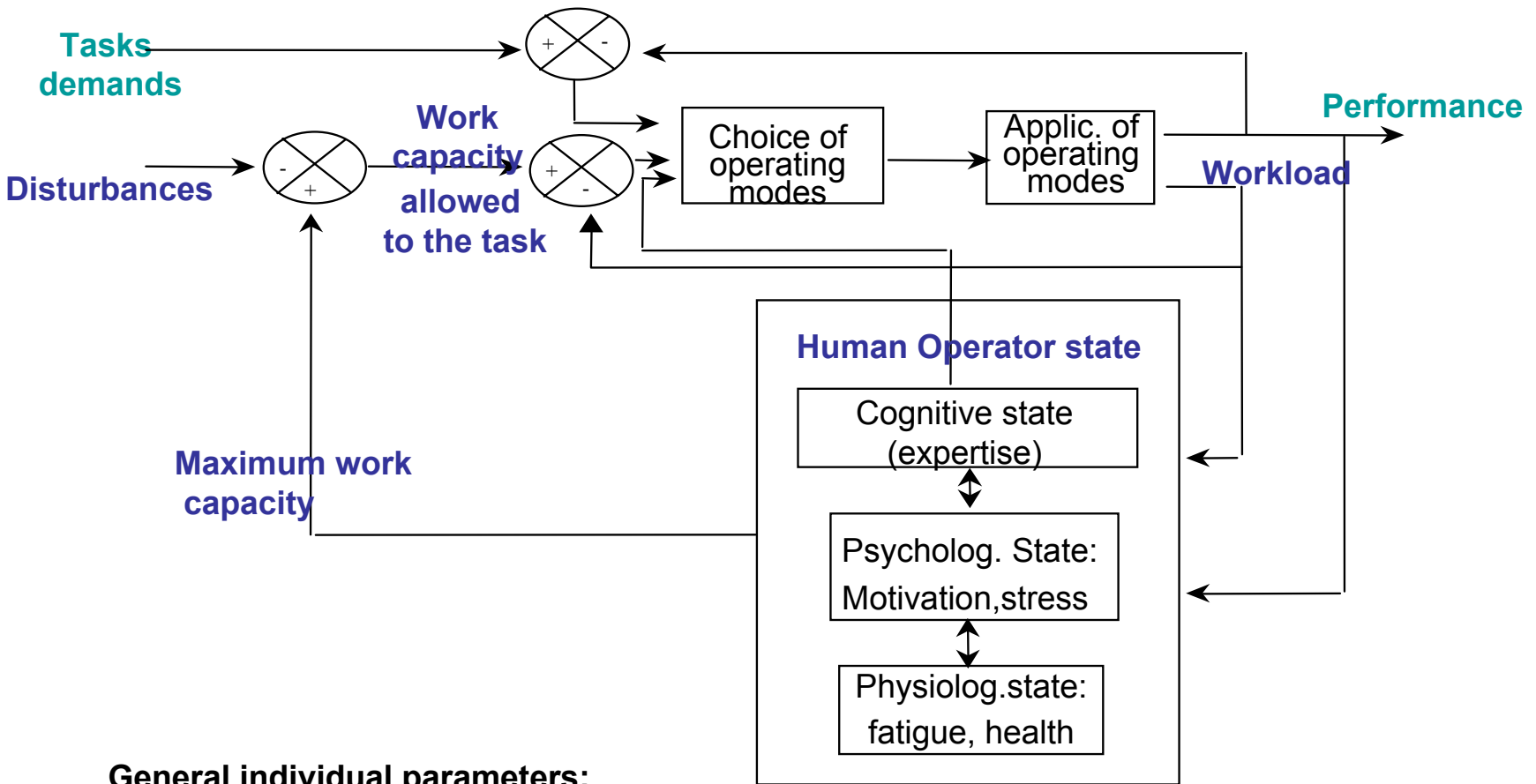
- **Model of Human Operators seen as system :**
 - . **control system (Johannsen, Govindaraj 80, Baron 68, 82)**
 - . **decision maker (Rasmussen 83, Millot 88, Hoc 96)**
- Identify their intrinsic capabilities and limits
- Define variables related to the human activity, human limits and capabilities , Foresse experimental measurements : workload, performance (Millot 88)
- Sharing the tasks to be performed between Human beings and Machines according to a double criterion (Millot 99) :
 - 1st task-sharing according to a criterion of technical feasibility
 - 2nd task-sharing according to a criterion of human feasibility



Rasmussen's step-ladder revisited (after Hoc 96)

Anthropocentered Pathway

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General individual parameters:
 Physical and mental capabilities
 Personal rythm of life

Parameters linked to the task:
 Biological rythms, social environmt
 -

**Individual Parameters for coping
 the task:** motivation, expertise...

**Model of the human
 activity regulation (Millot,03)**

Anthropocentered Pathway

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Sharing the tasks between Human and Machine

Defining the automation degree of the overall system :

T = set of the tasks to be performed

TA = set of the tasks which can be automated

TH = set of the tasks which cannot be automated

according to the criterion
of Technical feasibility

The ergonomic criterion creates 2 new classes of tasks :

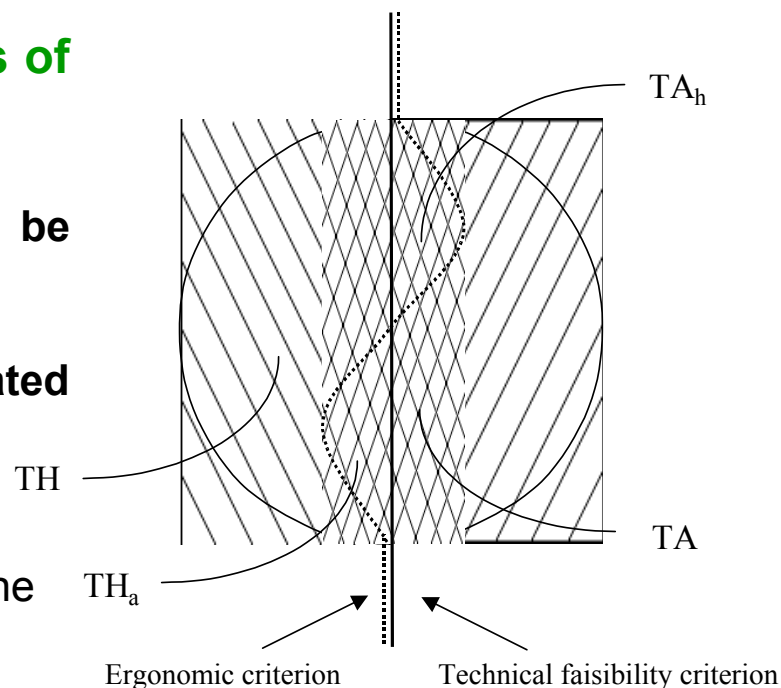
TA_h = Tasks which can be automated but to be allocated to the HO

(skill, responsibility...)

TH_a = not fully automated tasks but partially automated for assisting HO

(ex : ABS, diagnosis).

These classes can be used for defining a Human-Machine Cooperation.



Task Sharing/Cooperation

-Characteristics of Control-Tasks :

- Dynamic task allocation of the DOF of a Remote Control Arm
- Dynamic task allocation of the DOF of an automobile (lateral control, Automated Cruise Control...)
- « Skill Based Behaviour » in Rasmussen's ladder
- Very short response time (<1 second) the allocation must be imposed by an upper control system to both controllers human and machine.
- Once decided the allocation cannot be changed.

- Characteristics of Decision tasks :

- Longer response time (several minutes) : the tasks allocation can be cooperatively decided by both decision-makers human and machine.

Questions :

How to do this ? What capabilities must be integrated in the machine for doing so ?

A Definition of Cooperation (HOC, 96 ; MILLOT, HOC, 97)

Two agents **cooperate** when :

1. they **manage the interferences** between their goals (MI \approx coordination)
2. each agent acts in order **to facilitate** the other agent's goals (FG = Facilitating Goals)

An agent AGi has :

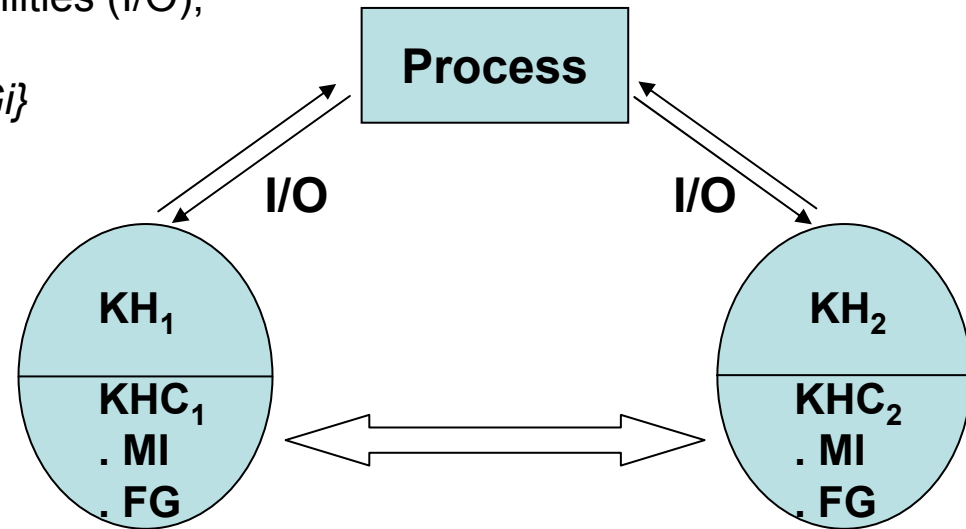
. A **Know-How** (KHi)

Knowledge, Reasoning capabilities,
Communication capabilities (I/O),

. A **Know-How to Cooperate** $KHC_i = \{M_i, FG_i\}$

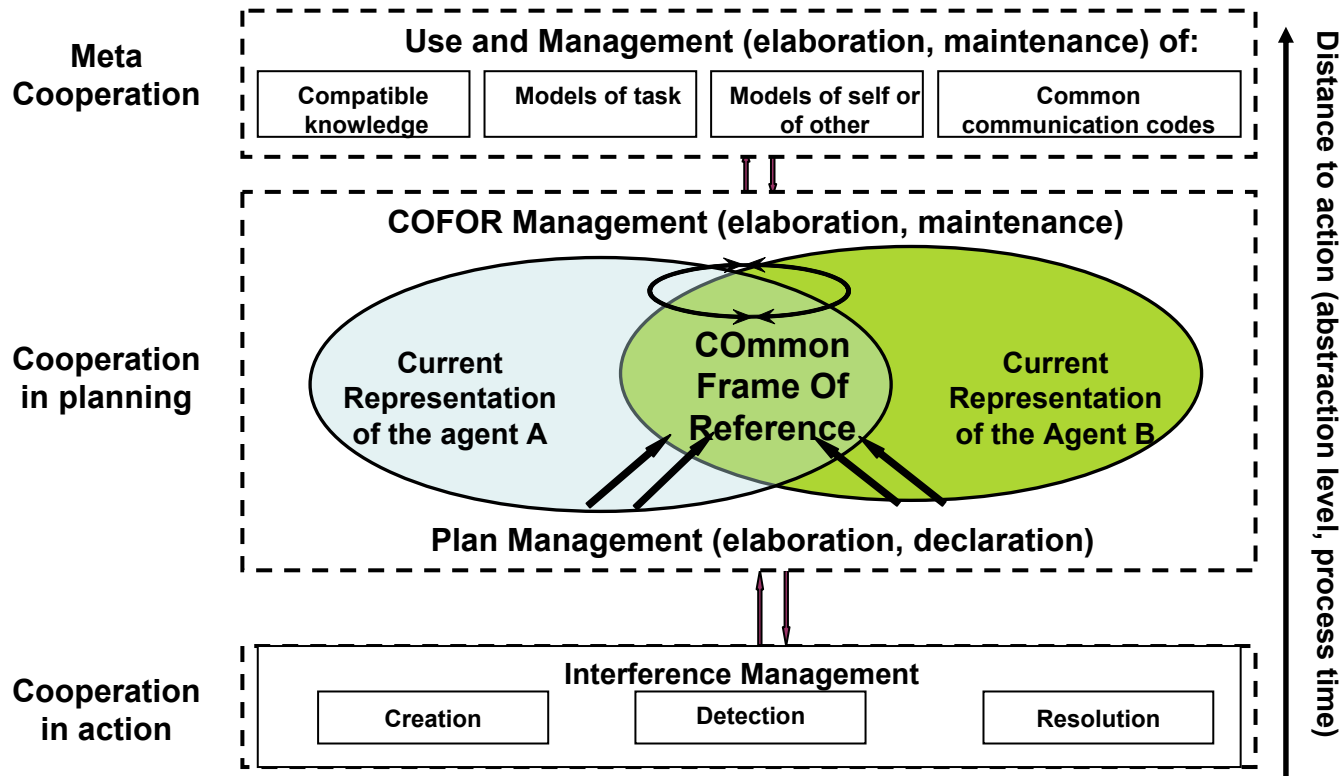
Questions :

- . Which **functions** for KHC ?
- . What **structure** for connecting the agent together and to the environment (I/O with the process, the rest of the world) ?



Cooperation Architecture

Hoc (2000, 2001) et Loiselet (Hélie & Loiselet, 2000)



Specifying the functions of the agent KHC, following 3 steps :

1. Defining these functions through the 3 cooperation forms defined by Schmidt (91)

- **Augmentative :**

- . Agents have **similar** KH_i
- . The task T can be **shared** into ST_j independant and similar

- **Debative :**

- . Agents have **similar** KH_i
- . T is **not shareable**

- **Integrative :**

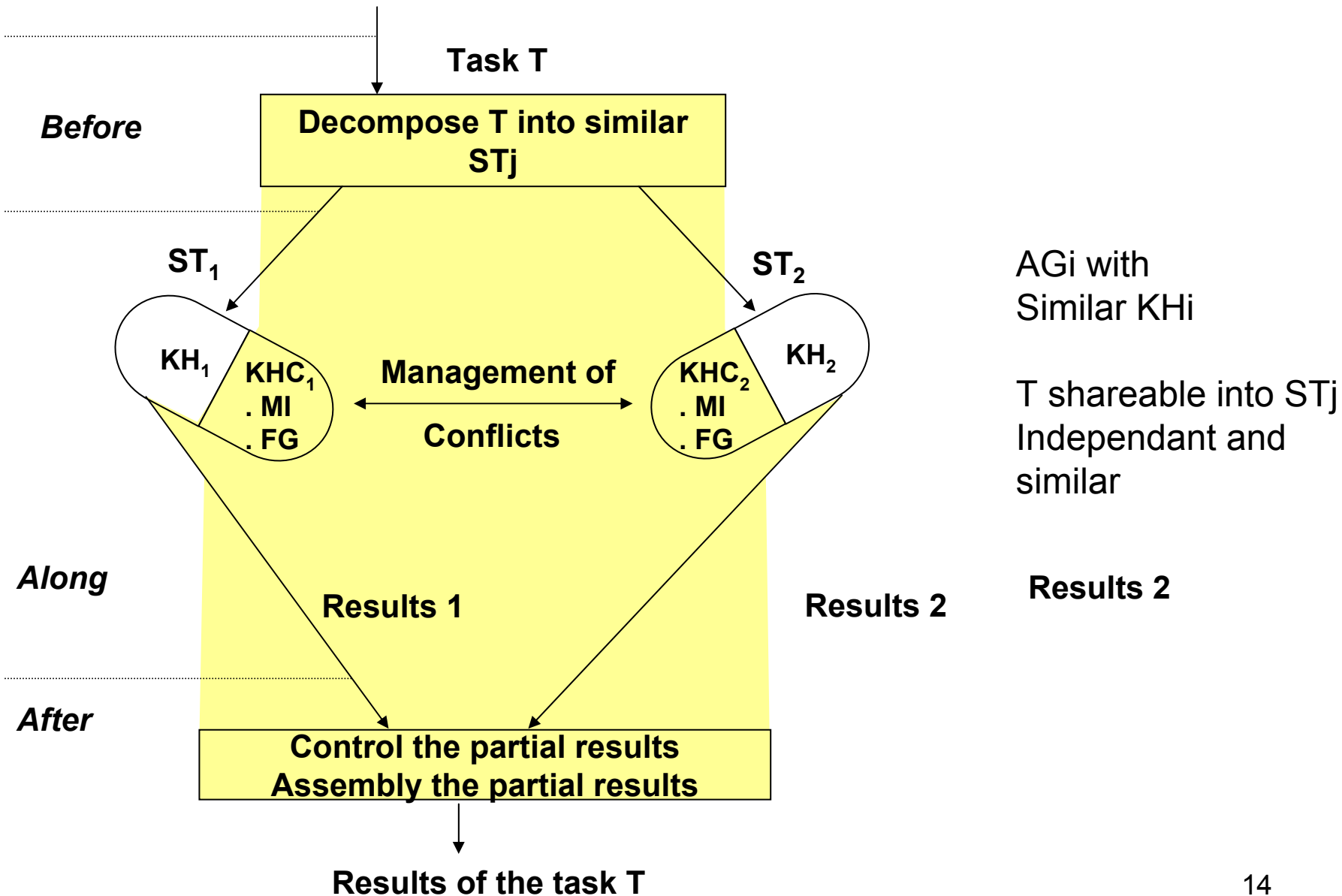
- . Agents **have different and complementary** KH_i
- . T is **shareable** into ST_j different and complementary

2. Showing these 3 forms are generic of all kinds of cooperation (Base)

3. Then the general function of a general cooperative agent could be built by adding the cooperative functions of each form :

$$KHC_i = KHC_{i_A} \cup KHC_{i_D} \cup KHC_{i_I}$$

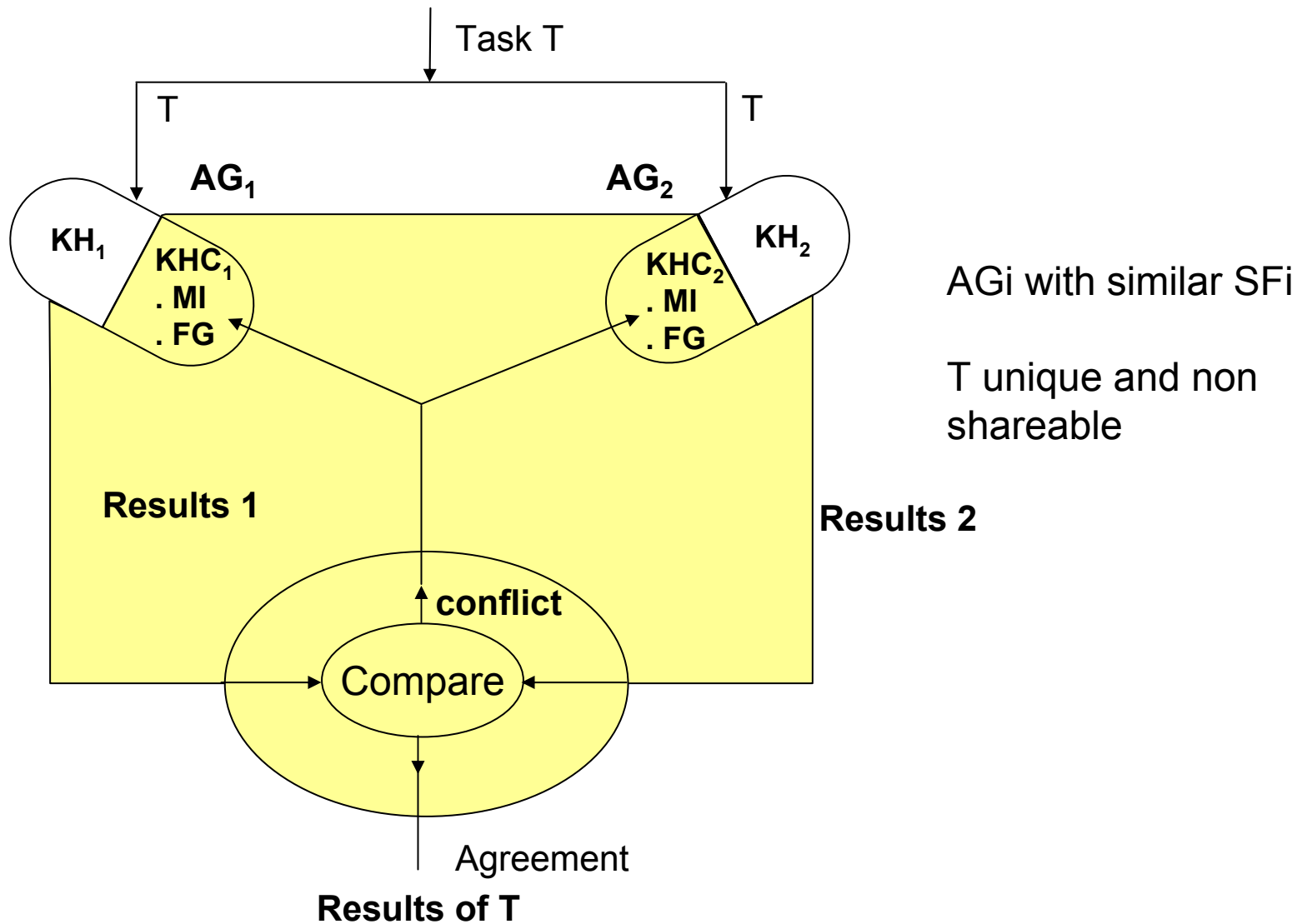
Augmentative Cooperation Form



Activities		Coordinator	AGx (vs AGy)
		KH: Task Context, -Defining a COFOR (from inference, from the passed experience) -Elaborating a global plan, decomposing the plan	KHx (vs KHy) : -answering the coordinator for building the COFOR -executing the sub-plan related to its own STi -detecting conflicts on resource with AGy (vs AGx)
Before	Decomposing T into STi	KHC MI : acquiring KHx and KHy	FG : transmitting its KHx (vs KHy)
	Allocating STi	MI : -acquiring WLx and WLy -allocating STi to AGx (vs AGy)	FG : -transmitting its WLx (vs WLx) -acknowledgement of its intention to perform STi
Allong	Managing conflicts between AGx and AGy on common resources	MI : -acquiring conflict signal from AGx or AGy -affecting priority to AGx (or AGy) -affecting resource to the other afterwards	FG : -informing coordinator on the occurrence of conflict -informing coordinator that the ressource is available
After	Recomposing/controlling the results	MI : -acquiring results (contexts) from AGx and AGy -controlling results (contexts) form AGx et AGy	FG : -transmitting results (context) to coordinator -transmitting sub-plan (sub-goal) to coordinator

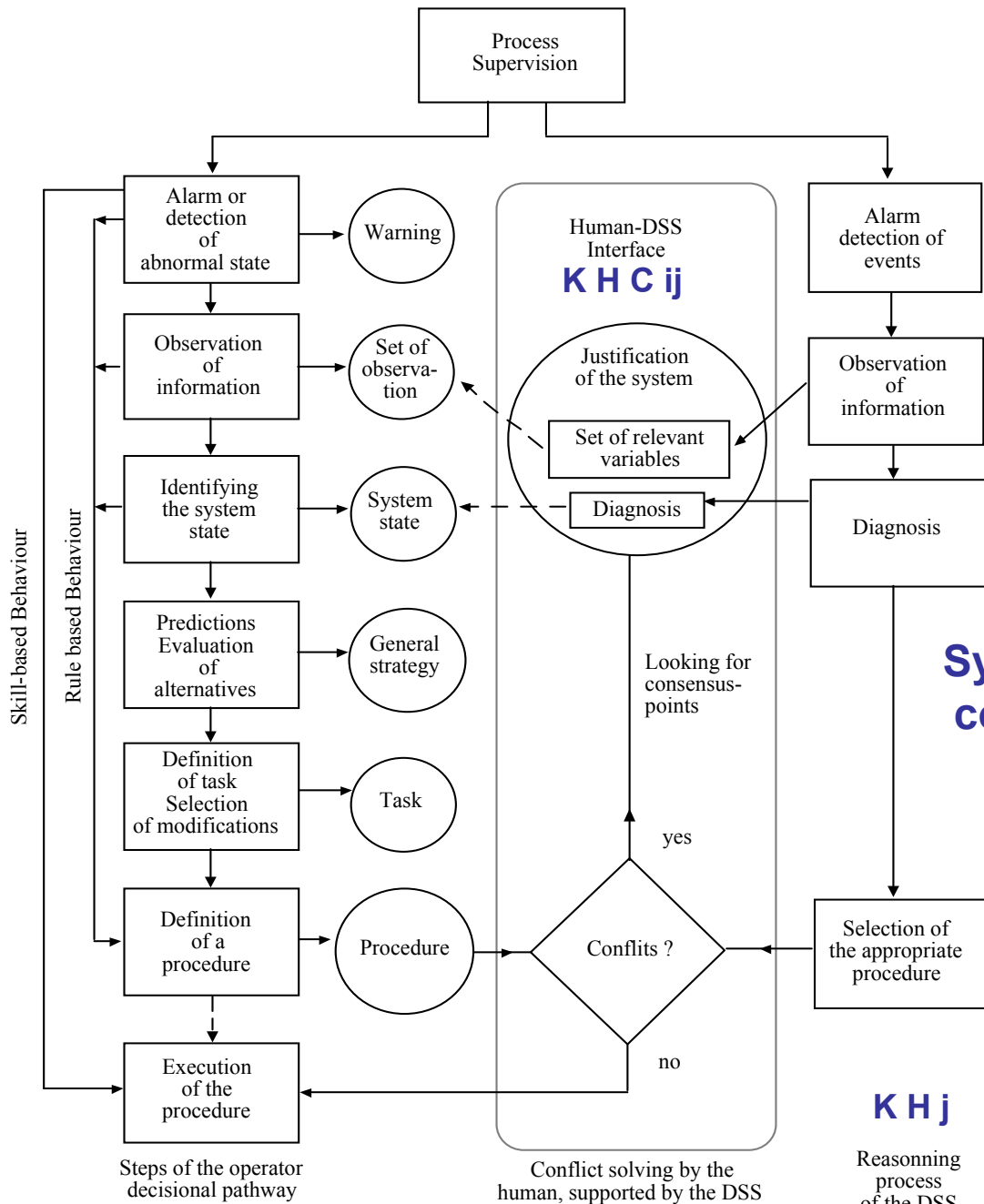
Table 1 : Summary of KHC activities (MI, FG) of the agents in an augmentative cooperation

Debatative Cooperation form



Activities	AGx (vs AGy)
	KH : task context -Defining a COFOR (from inference, from the passed experience) -elaborating a plan
Preparing cooperation	KHC : MI : acquiring (infering) KHx (vs KHx) FG : transmitting its KH to the other
Comparing results (even partial)	KHC : MI : acquiring results from AGy (vs AGx) FG : transmitting results to AGx (vs AGy) MI : -understanding results from AGy (vs AGx) -comparing with its own results, -deciding : agree, disagree
Conflict solving	KHC : MI : acquiring AGy's (vs AGx) plan and view-point on task context FG : transmitting its own plan and view on the context to the other MI : -comparing both contexts and plans -deciding on the conflict persistence FG : accepting its own error and drawing the lesson

Table 2 : Summary of the KHC activities of the agents (MI, FG) in a debative cooperation



Synthesis of the decisional conflict pathway between the HO and the DSS

KHj

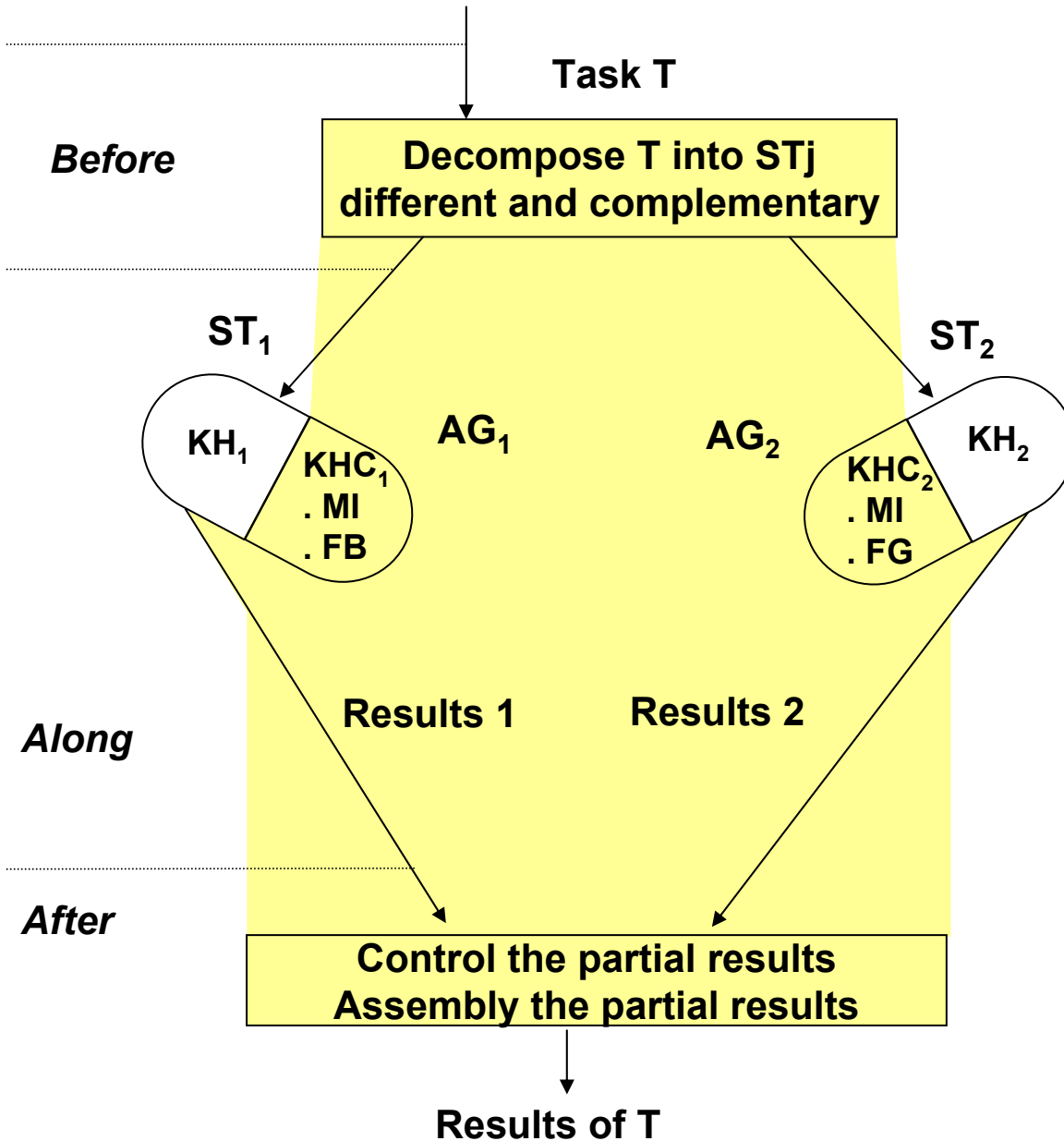
Reasoning process of the DSS

KHi

Steps of the operator decisional pathway

Conflict solving by the human, supported by the DSS

Integrative Cooperation Form



AG_i with SF_i
 . different
 . Complementary

T shareable into ST_j
 . different
 . complementary

Activities		Coordinator	AGx (vs AGy)
		KH : Task Context, -Defining a COFOR (from inference, from the passed experience) -Elaborating a global shared plan, -Decomposing the global plan into sub-plans (STi)	KHx (vs KHy) : -answering the coordinator for building the COFOR -executing the sub-plan related to its own STi -correcting its STi if required by the coordinator
Before	Decomposing T into STi	KHC : MI : acquiring (infering) KHx and KHy	KHC : FG : transmitting its KHx (Vs KHy)
	Allocating STi	MI : -acquiring WLx and WLy -allocating STi to AGx (vs AGy)	FG : -transmitting its WLx (vs WLy) -acknowledgement of its intention to perform STi
Allong	Controlling partial results	MI : -acquiring partial results (context) -comparing results to plan and to sub-plans -ordering corrections to AGx or AGy if needed	FG : -transmitting (partial/results context) to coordinator -correcting the STi if asked by the coordinator
After	Recomposing/Controlling the results	MI : -acquiring results (context) -controlling results (context) -ordering corrections to AGx or AGy if needed	FG : -transmitting results (context) to coordinator -correcting the STi if asked by the coordinator

Table 3 : Summary of the KHC activities (MI, FG) of the agents in an integrative cooperation : Case of a shared plan elaborated by a coordinator

Genericity of the 3 cooperation forms by Schmidt

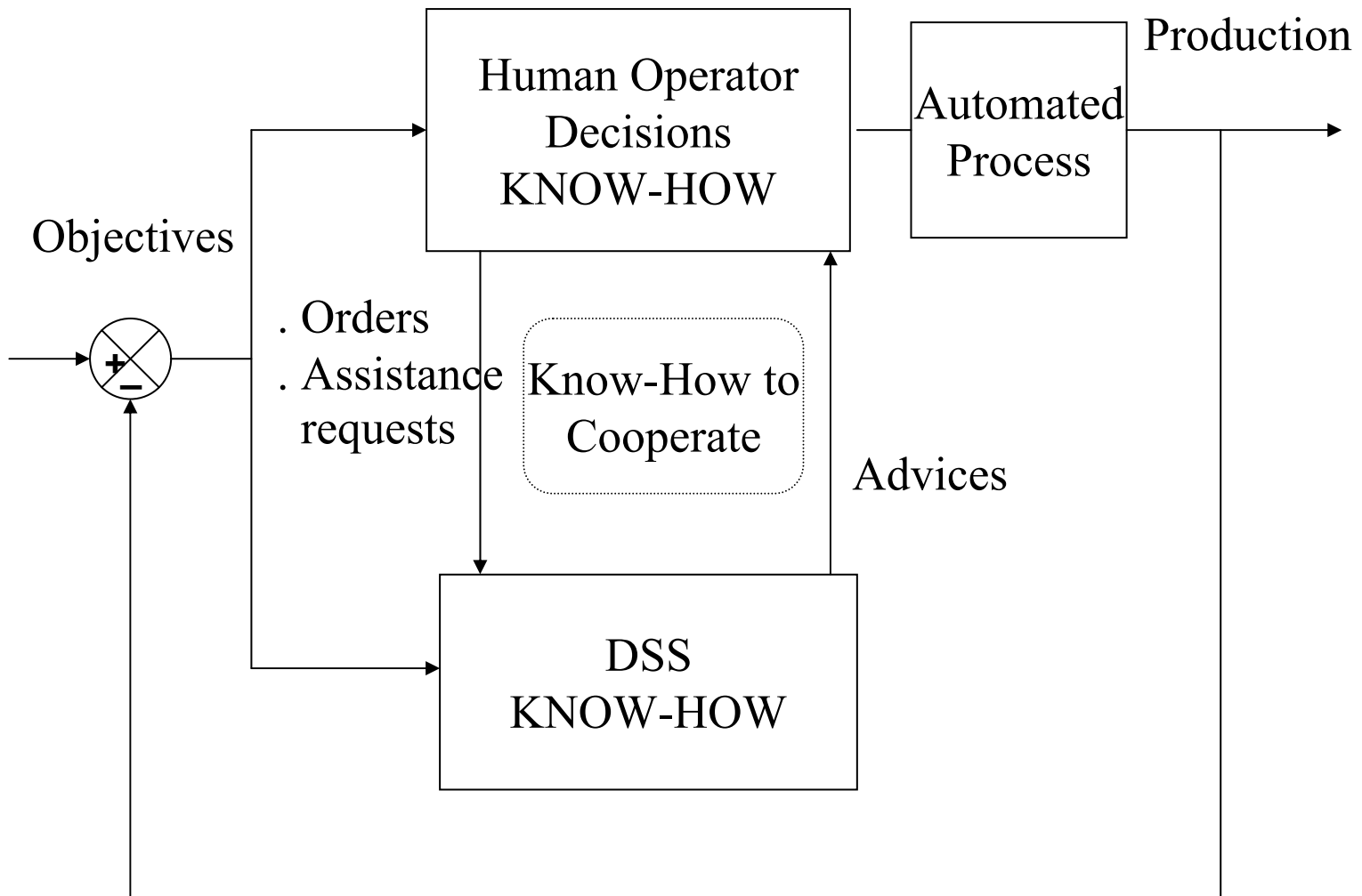
2 agents AGi (KHi, KHci)

1 task T

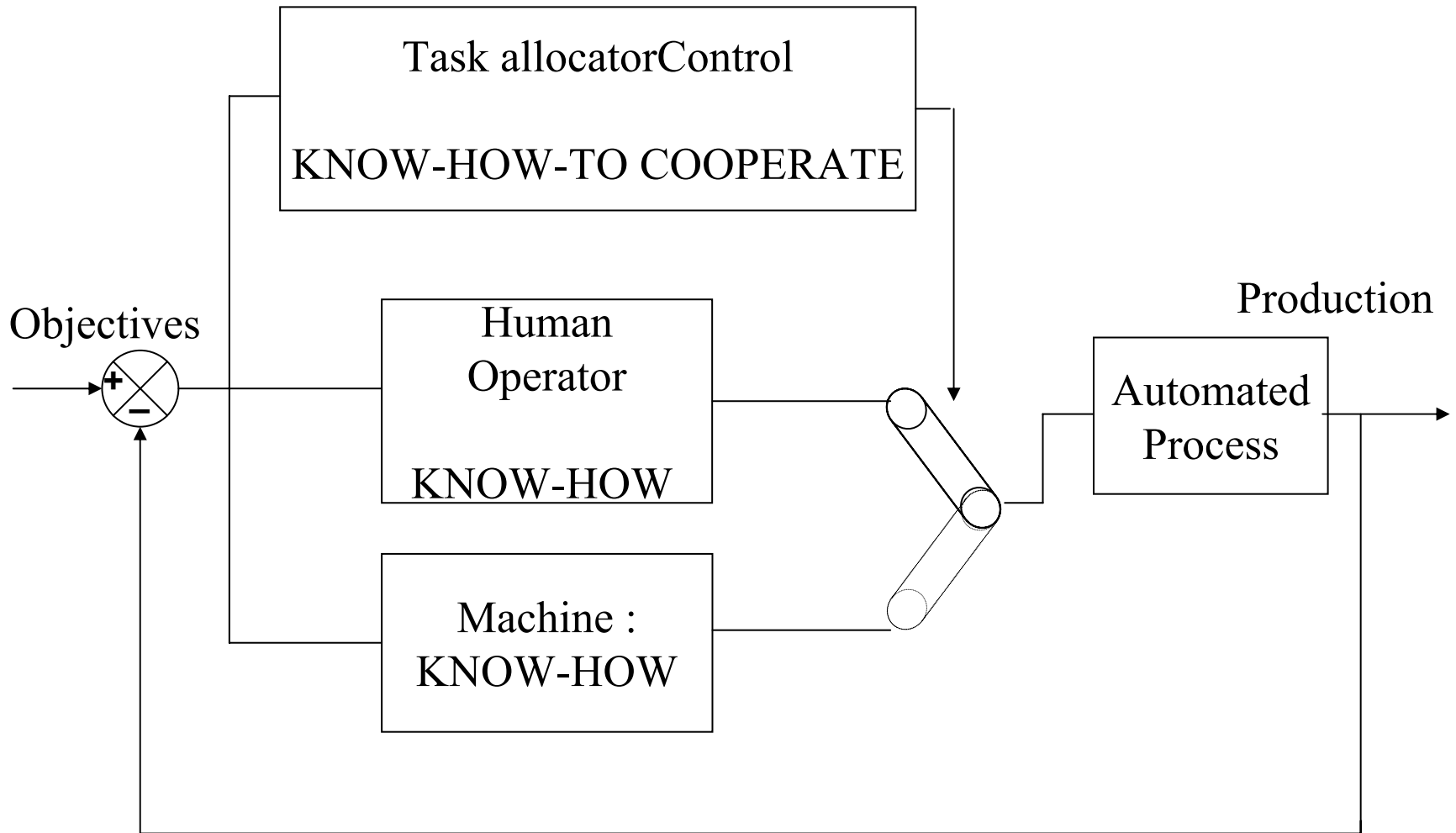
		Similar KHi	Different KHi
Shareable Tasks	Similar STj	Augmentative	Cooperation impossible
	Different STj	Cooperation impossible	Integrative
Non-shareable Tasks		Debatative	Cooperation impossible

All kind of cooperation is a combination of the 3 cooperation forms by Schmidt

<p>Adequacy of Agi</p> <p>Task shareability</p>		<p>Similar KHi</p>	<p>Different KHi</p>
<p>Shareable Tasks</p>	<p>Similar STj</p>	<p>Augmentative</p>	<p>Cooperation impossible</p>
	<p>Different STj</p>	<p>Cooperation impossible</p>	<p>Integrative</p>
<p>Non-shareable Tasks</p>		<p>Debatative</p>	<p>Cooperation impossible²²</p>



Vertical structure for a H-M Cooperation



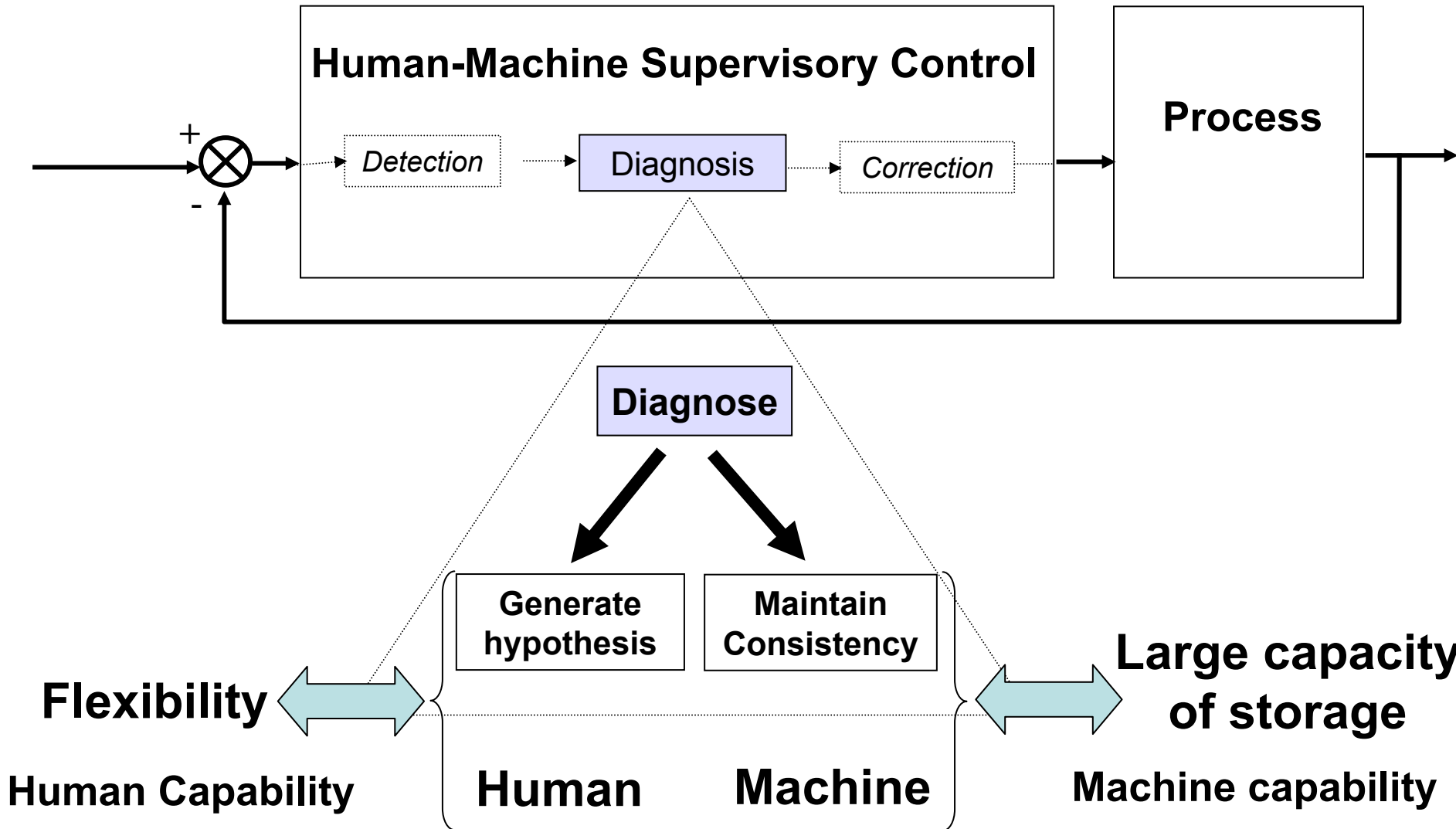
Horizontal structure for a H-M Cooperation

These 3 forms have been implemented and tested in several applications

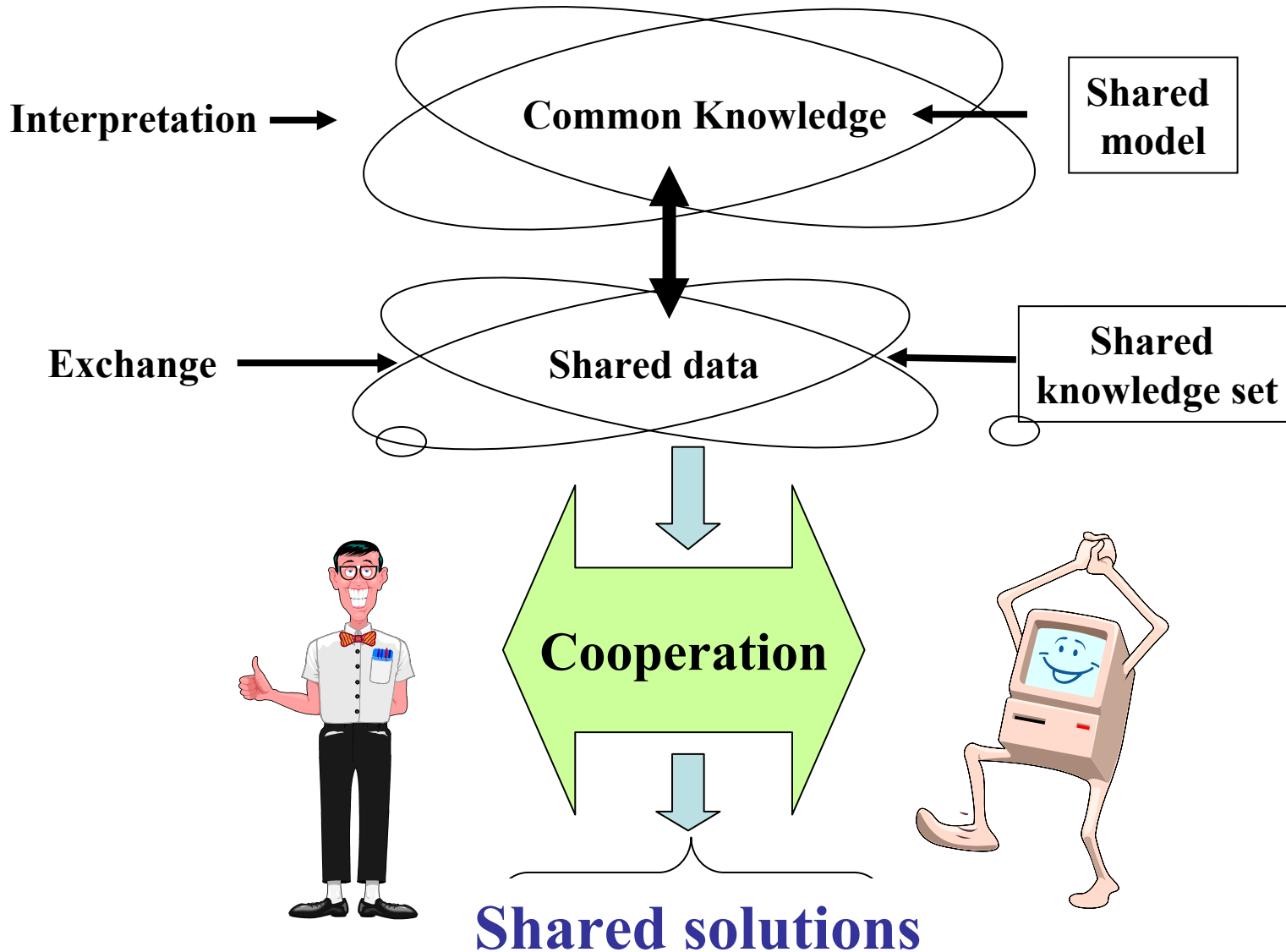
- Diagnosis support system for a telephone network
(Jouglet, Vanderhaegen, Millot, 01).
- Dynamic Task Allocation between Human and DSS in the ATC domain
 - . Augmentative form (Debernard, Vanderhaegen, Millot 1993)
 - . Multi-form (Guiost, Debernard 2004)

**Example of integrative Cooperation
applied to
the diagnosis of a telephone network**

The diagnosis tasks

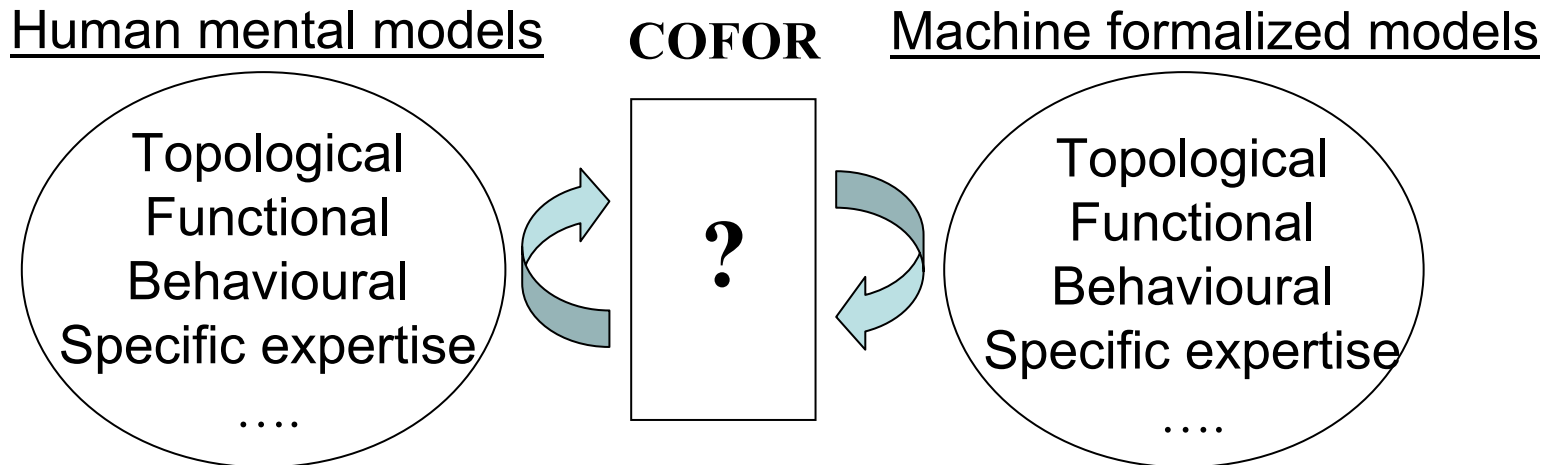


COFOR : COmmon Frame Of Reference [Hoc 1997]



What kind of knowledge in the COFOR ?

Different view-points are used by both human and machine to diagnose

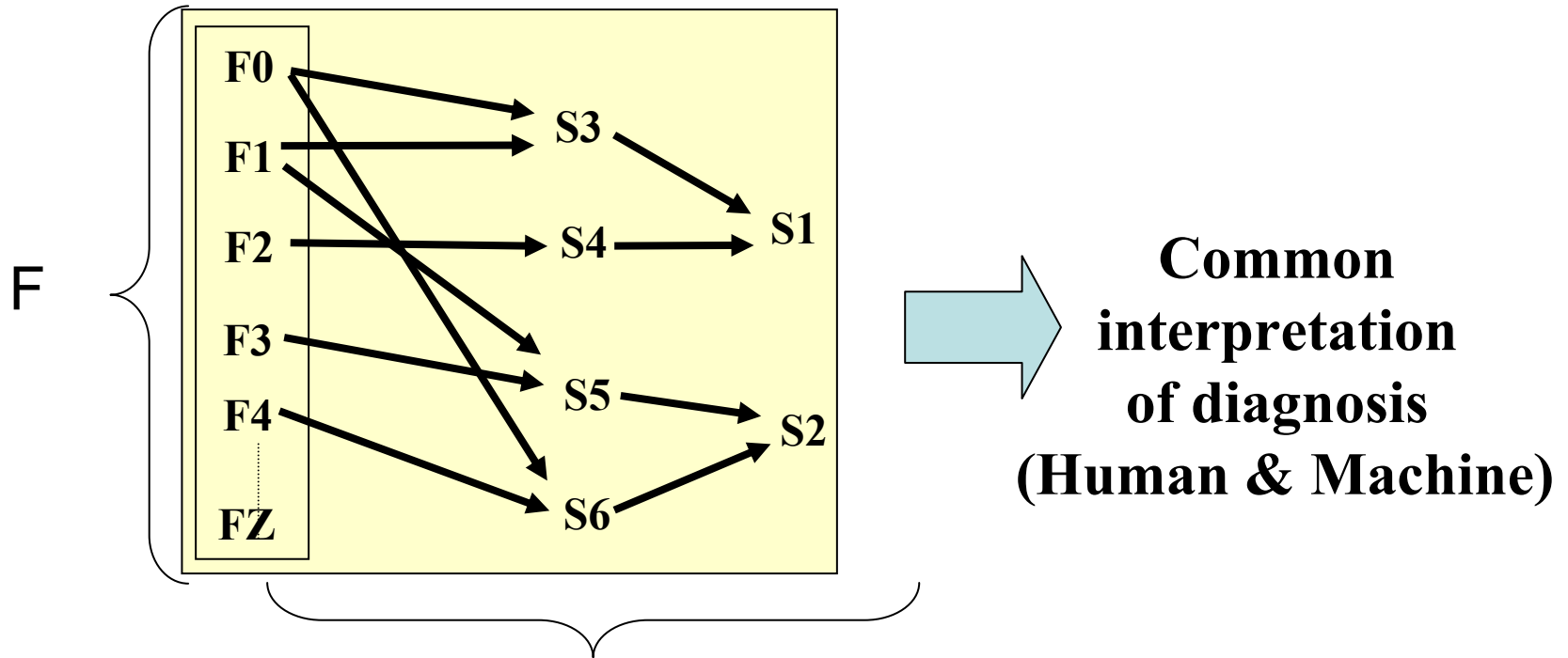


Questions :

- Should knowledge shared in COFOR be uniform (human v.s. machine) ?
- Does the human-operator use particular kind of knowledge in some situations?
- What kind of knowledge should be integrated in COFOR for making cooperation easier?
-?

A causal graph as a unique format for all view-points

Failures (F_i) $\xrightarrow{\text{Causal relations}}$ Symptoms (S_j)

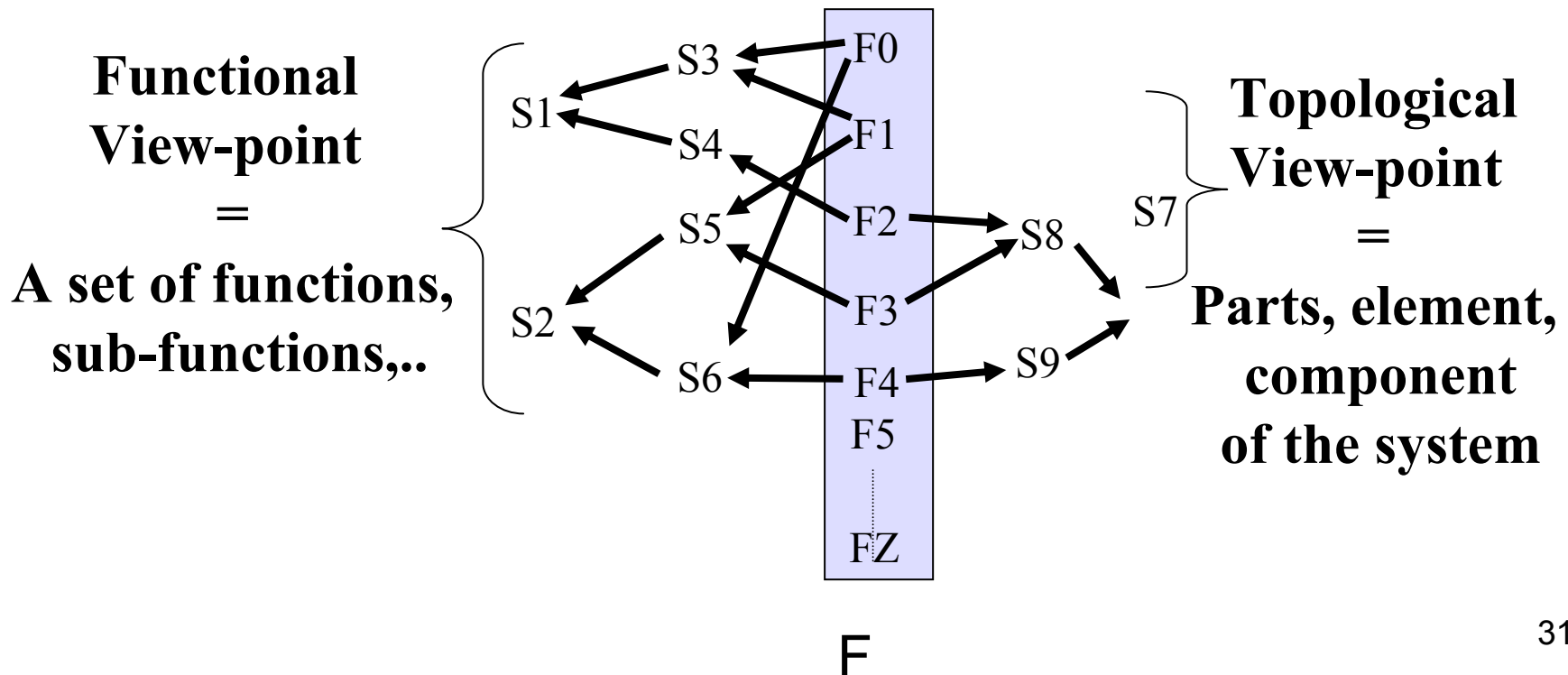


Set of all shared knowledge (topological, functional...) = A unique causal graph

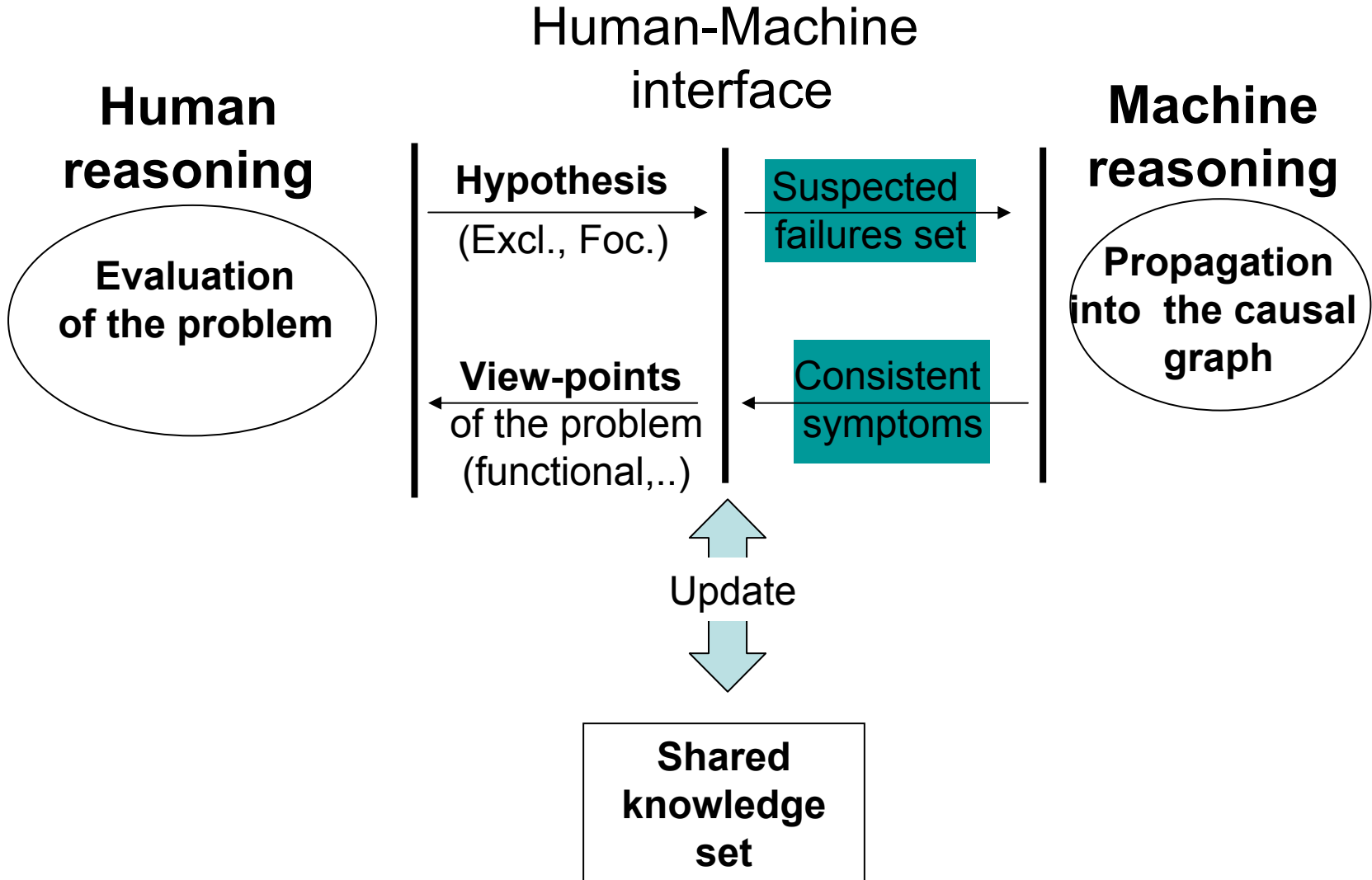
Different view-points through the causal graph

A causal graph for different view-points

- The view-points of the system are linked to a unique set of failures (F)
- Each view-point (e.g. functional) is a hierarchy of symptoms



Cooperative reasoning

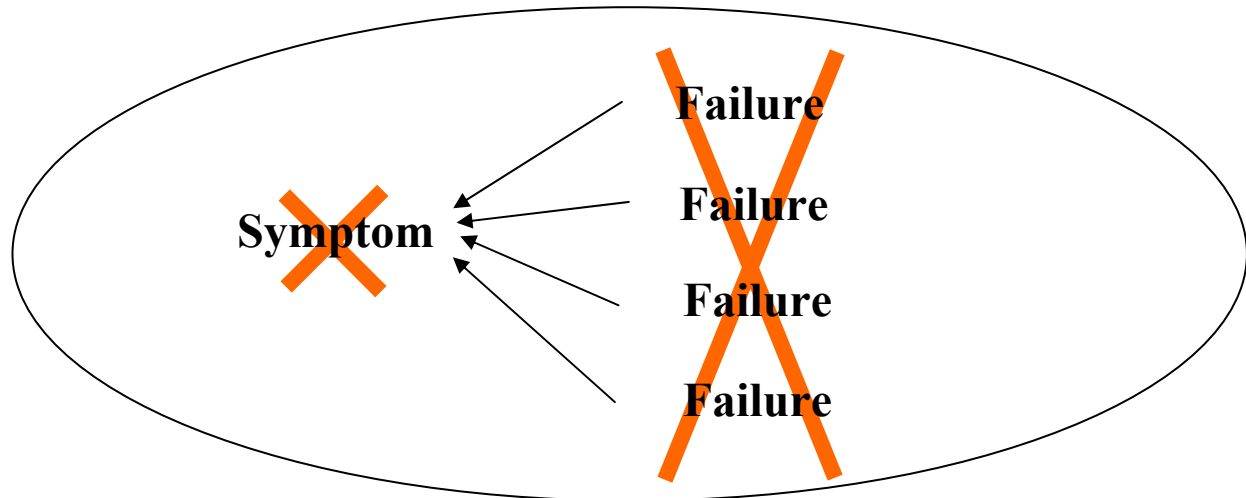


Reasoning on graph with causal implication

Using implication on causal relation :

$$\text{Failure} \rightarrow \text{Symptom} \equiv \neg \text{Symptom} \rightarrow \neg \text{Failure}$$

Part of the
causal graph



An excluding operator Excl() is defined to consider symptoms which do not affect the process and to determine unsuspected failures:

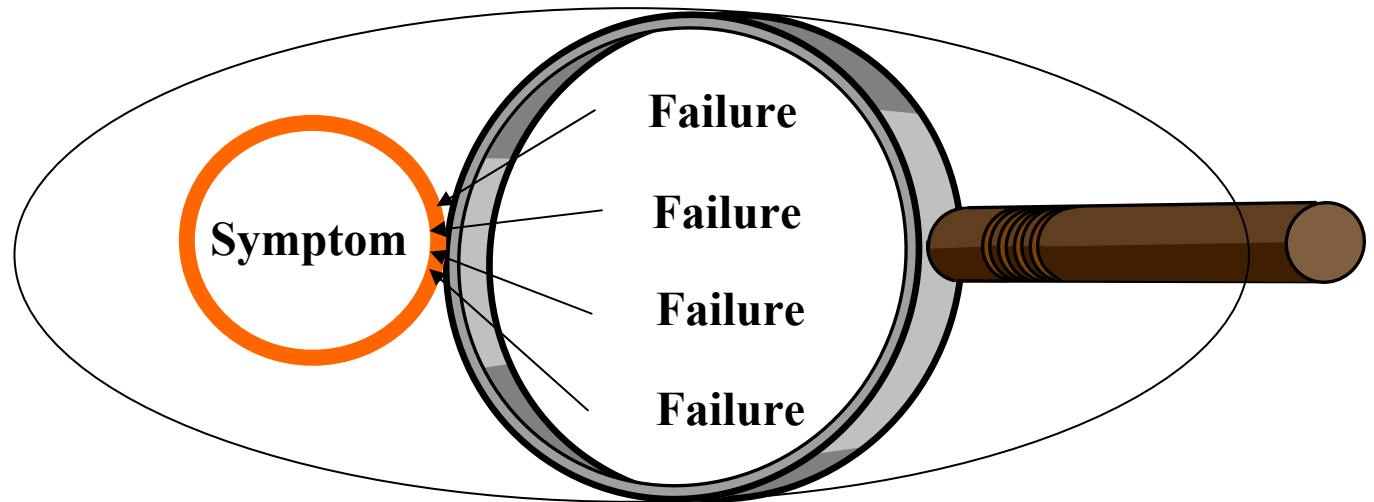
$$\forall S(H_p, K) \in \Phi \quad H_p, F, E_{i+1} = \text{Excl}(S(H_p, K), E_i) = E_i - \text{Failure}(S(H_p, K))$$

Reasoning on graph with causal abduction

Using abduction on causal relation :

Failure \rightarrow Symptom , Symptom $\overset{\text{Abd.}}{\dashv}$ Failure [Poole 1992]

Part of the
causal graph

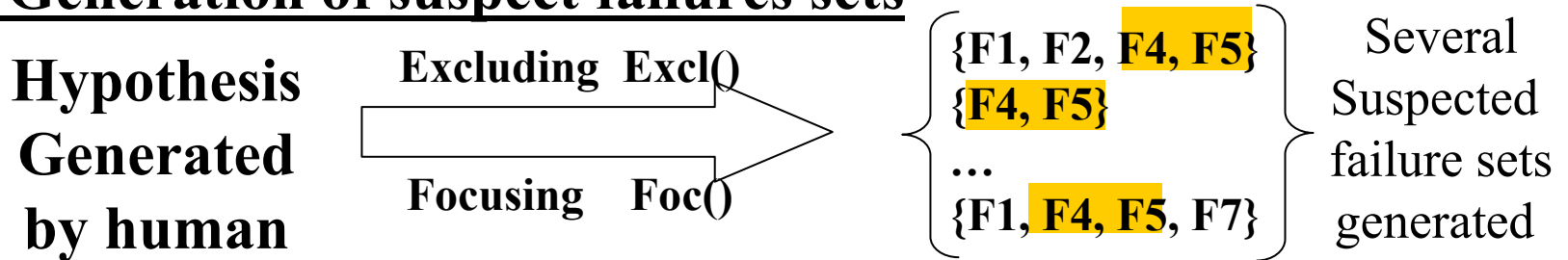


A focus operator $Foc()$ is defined to consider symptoms affecting the process and to determine suspected failures:

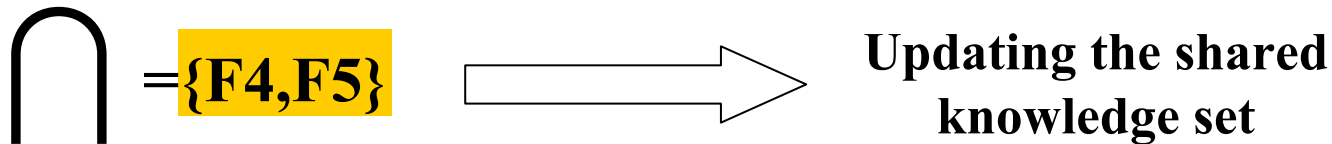
$$\forall S(H_p, K) \in \Phi(H_p, \mathbf{F}), E_{i+1} = Foc(S(H_p, K), E_i) = E_i \cap Failures(S(H_p, K))$$

Global application of the defined operators

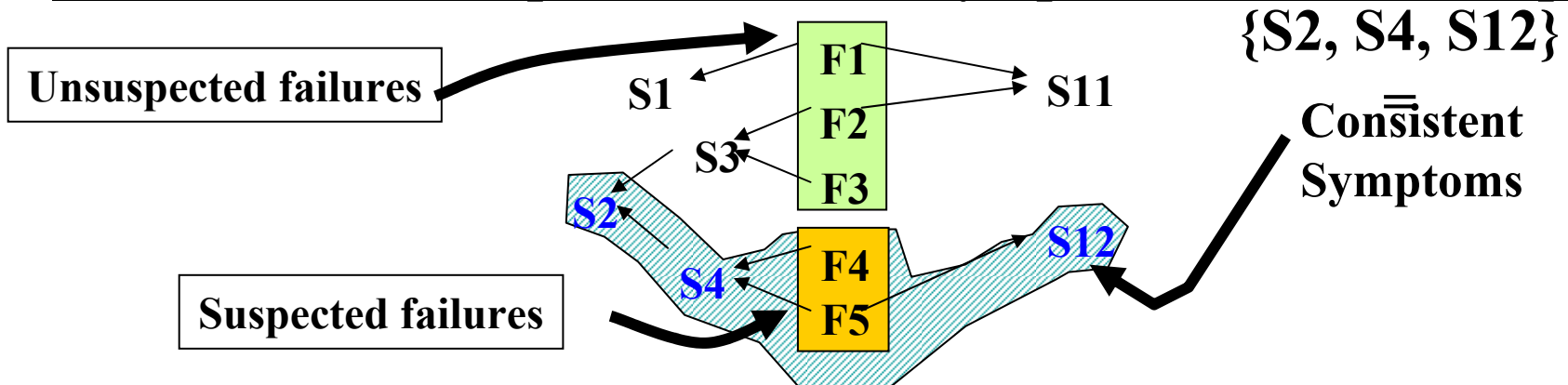
- Generation of suspect failures sets



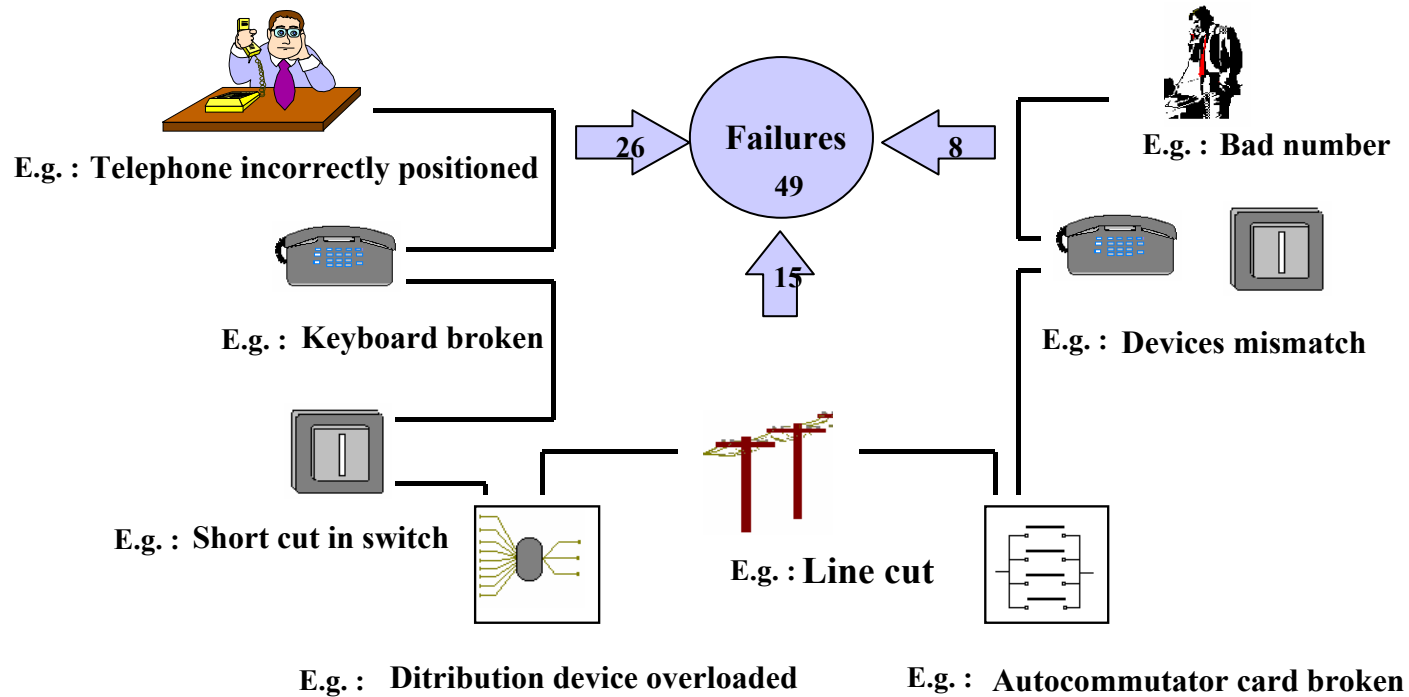
- Maintain the global reasoning consistency



- Propagation into the causal graph in order to make symptoms consistent with suspected failures (symptoms that should appear)



Application to a telephone network diagnosis



49 Failures

Five view-points of the system

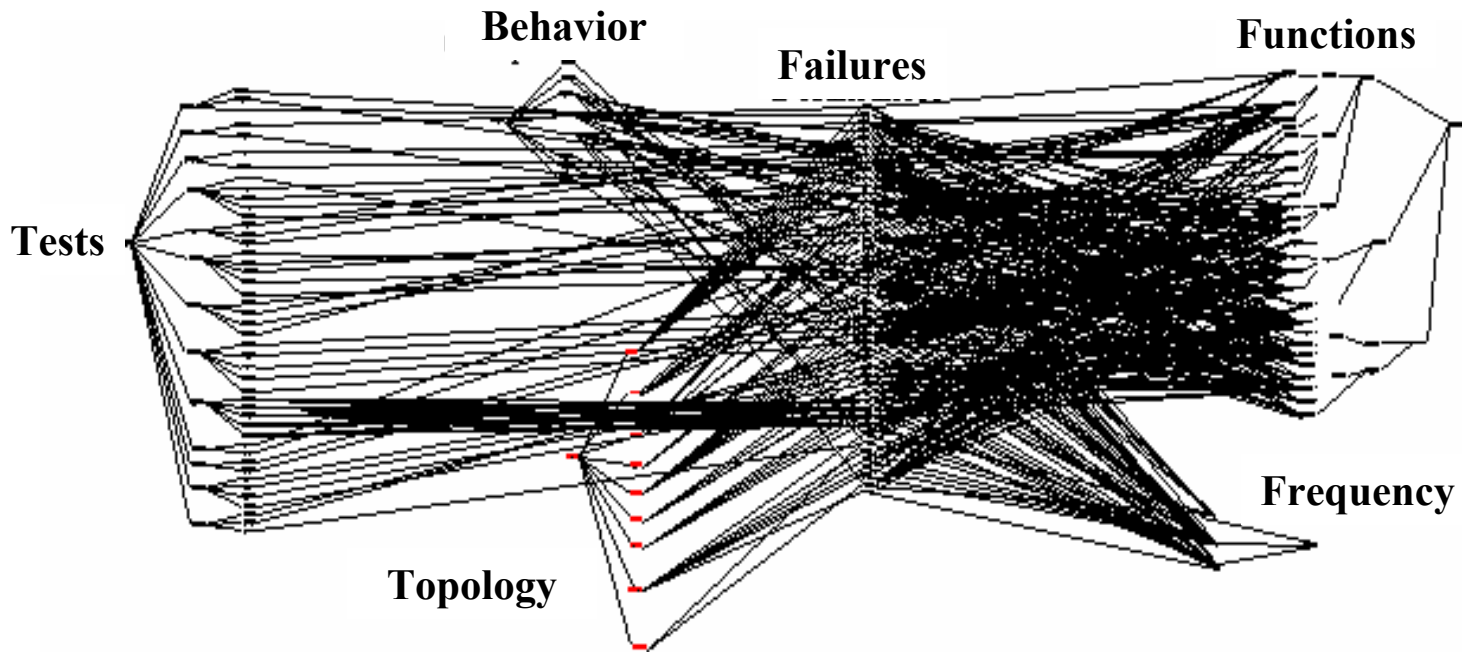
**5
view-
points**



**• 500
causal
links**

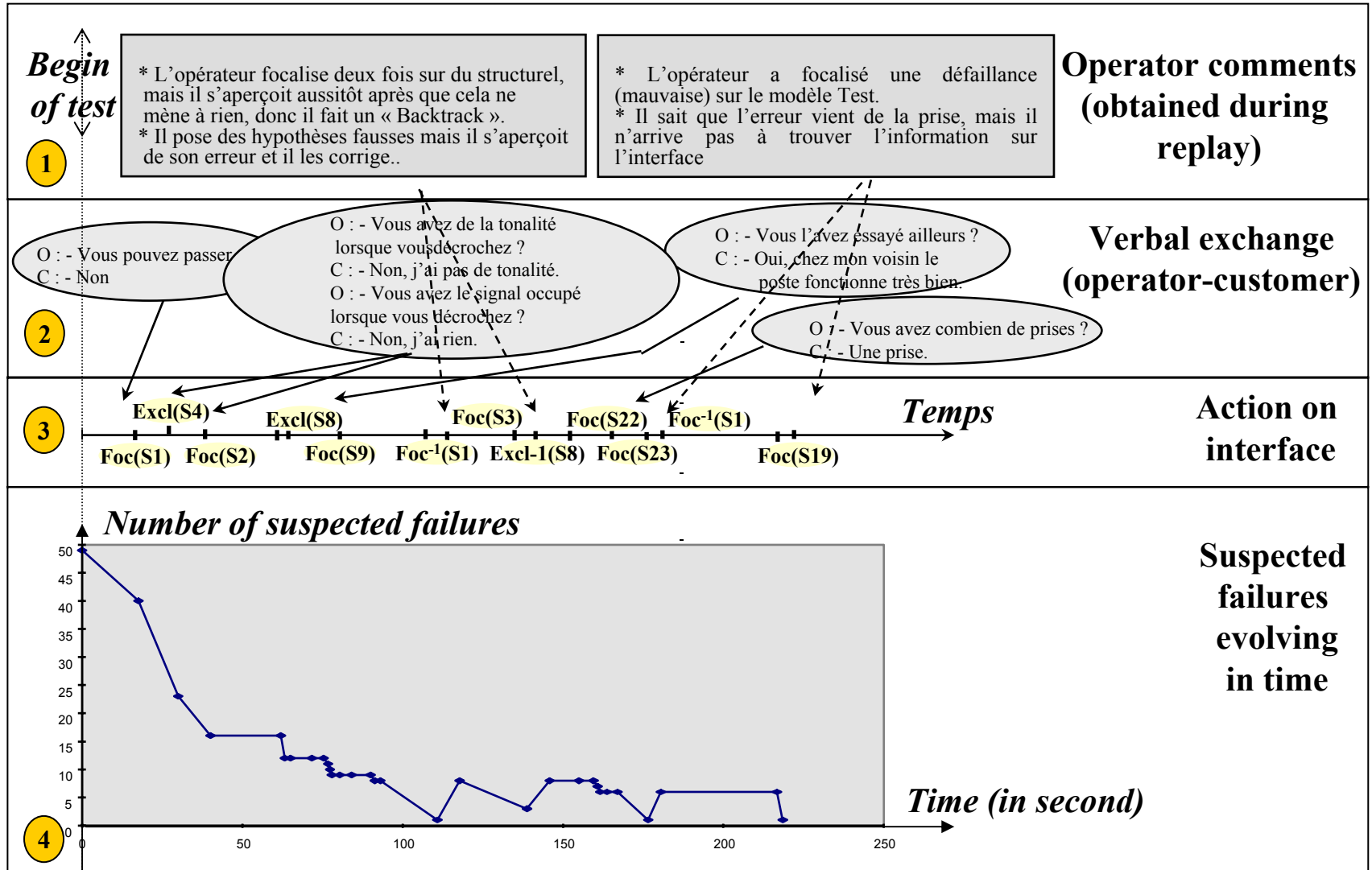
**• 120
terminal
nodes**

Topological → Elements, parts, components
Functional → Function, sub-functions available (or not)
Behavioural → Typical malfunctioning symptoms
Tests → Test available
Frequency → Frequency of the failure occurrence

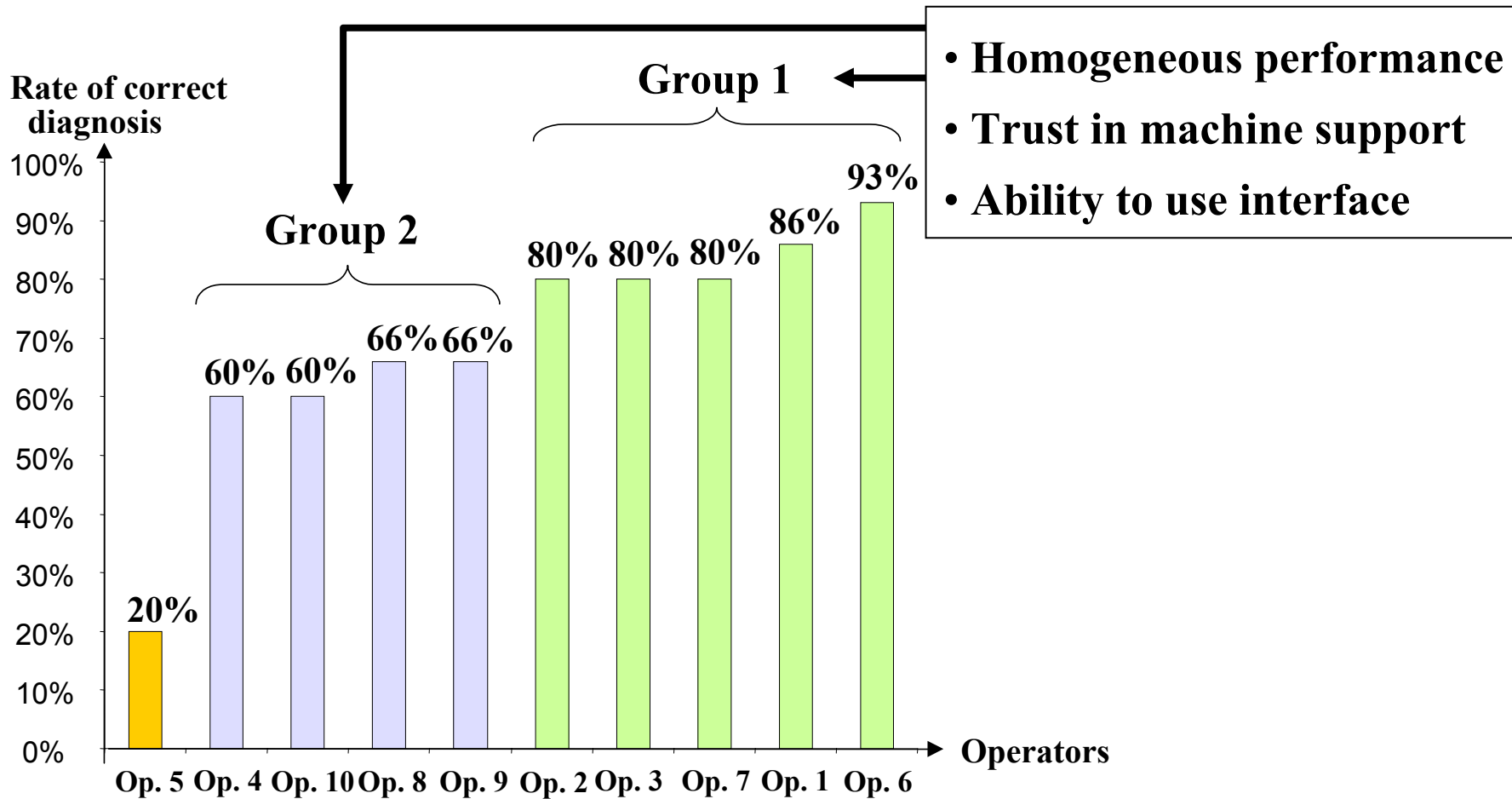


Causal graph

Synthesis of collected data



Human-machine team performance



Success of diagnosis with or without correcting

Correct diagnosis = 75,4%		Wrong diagnosis = 24,6%	
Without correction	With a correction	With a correction	Without correction
57,5%	17,9%	18,6%	6%

Success of the integrative cooperation

Limits :
 • **Errors were detected**

Problem :
 • **Errors not detected**

36,5%

Several errors still remain undetected or difficult to be corrected by operator

Cooperation was usefull

Partial results : 3 operators X 15 cases (constraint in real situation)

	Human-machine cooperation	Human alone
Correct Diagnosis	82%	64%
Time	2 min. 11 sec	2 min.

Efficiency increased

Temporal cost very low

View-point using rate

Frequency	Topological	Functional	Behavioral	Tests
0,7%	15,5%	38%	20,6%	25,2%

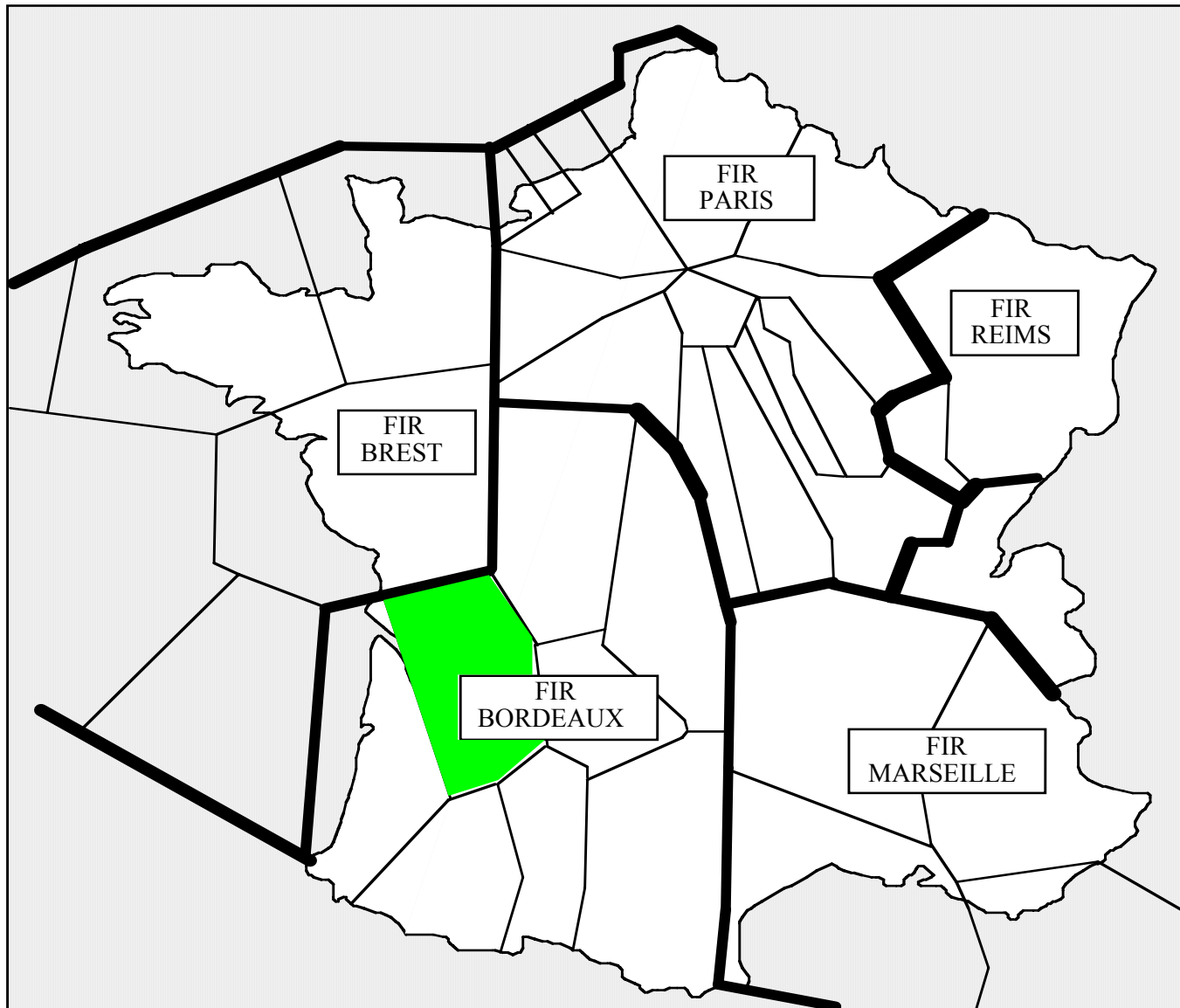
- **Misunderstood**
- **Not very usefull for human operators**

- **4 view-points were useful and used**
- **Complementarity of view-point**
- **Flexibility of switching between view-point during reasoning**
- **Similar to human mental models**

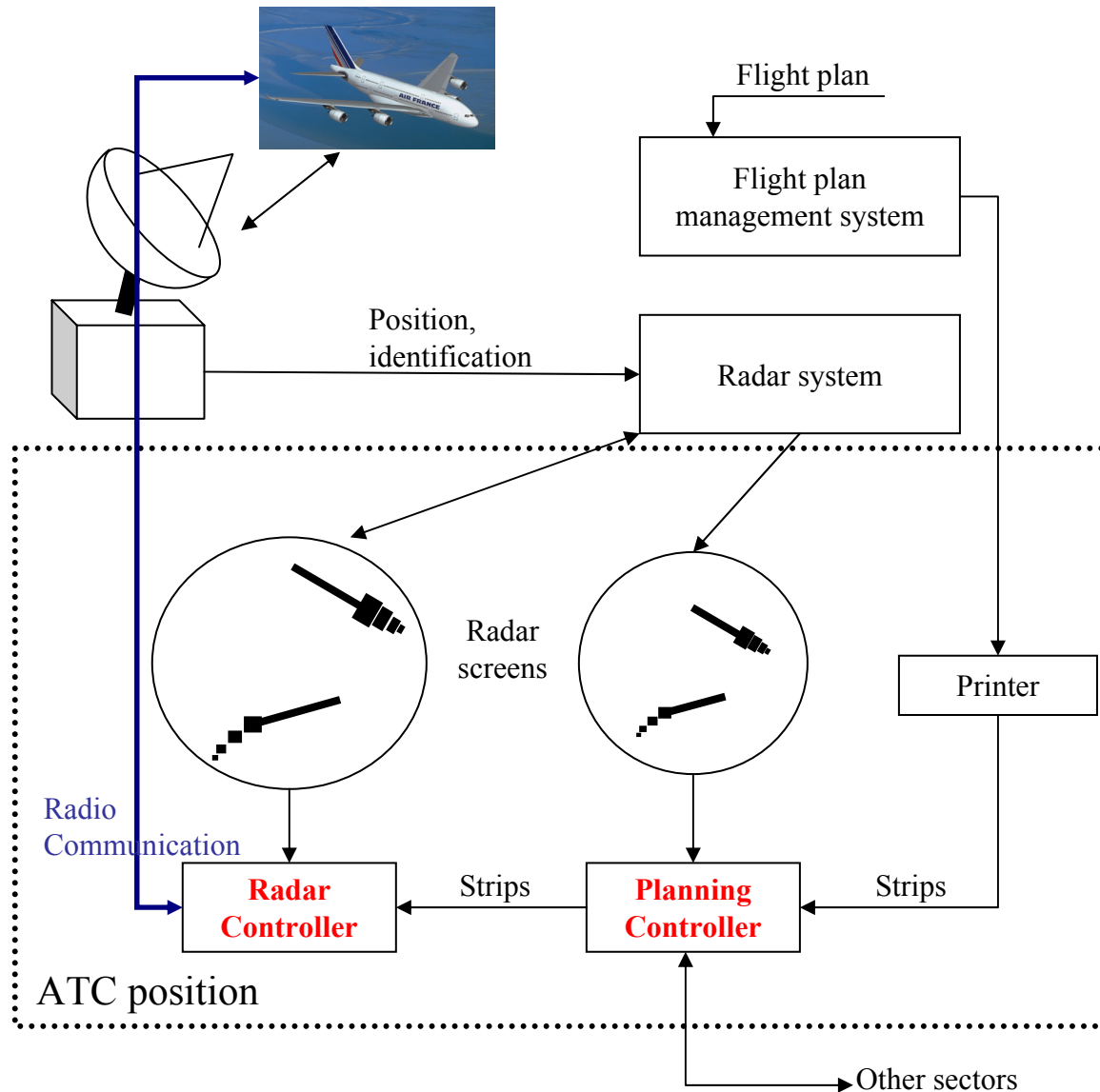
Operators ' comments

Example of Cooperation in the Air Traffic Control

Organisation of the French Air-Traffic Control



Organisation of the French Air-Traffic Control





SIMUL

PSE H1

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H1 H2 H3 Z1

11:58 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100



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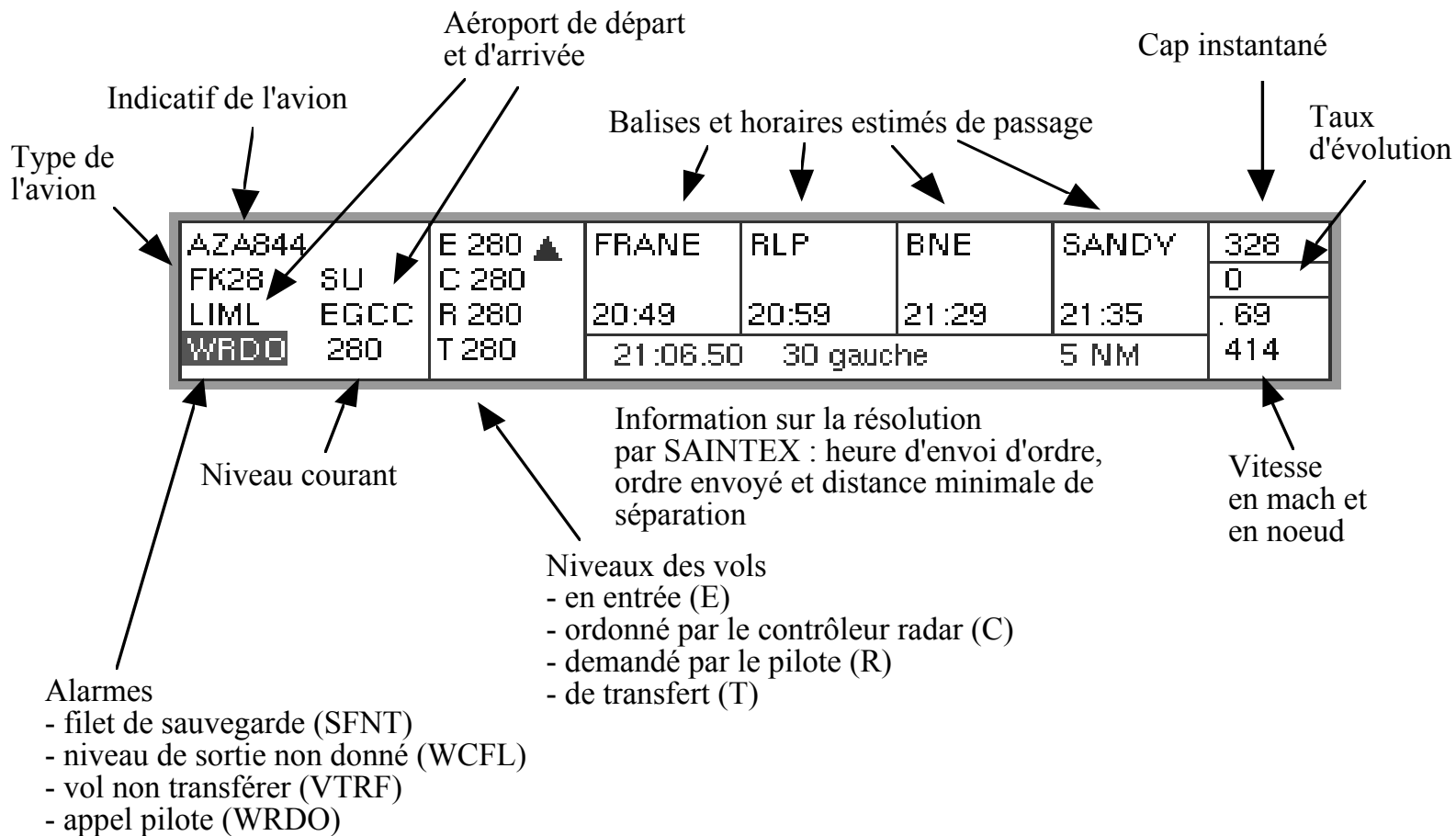
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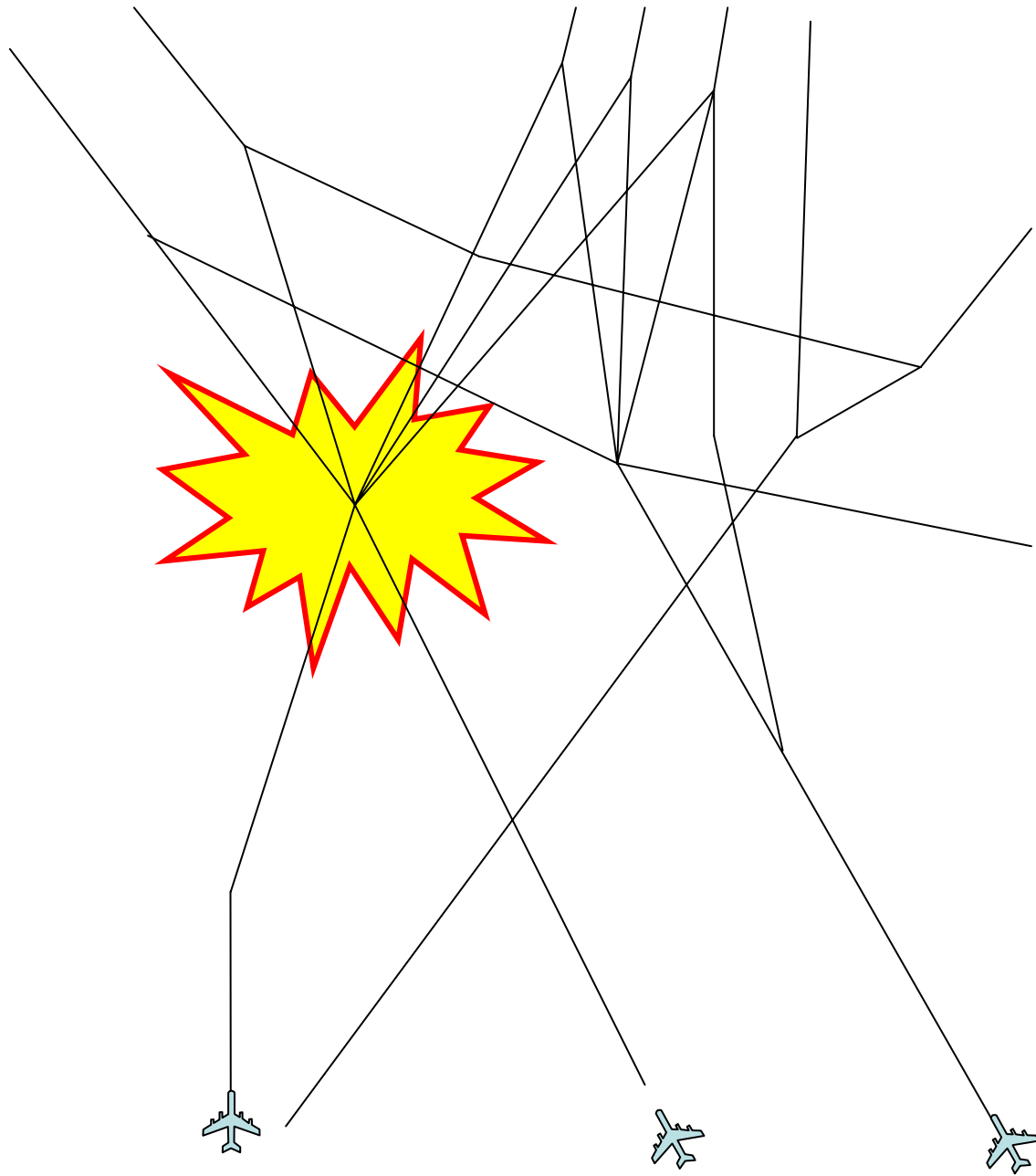
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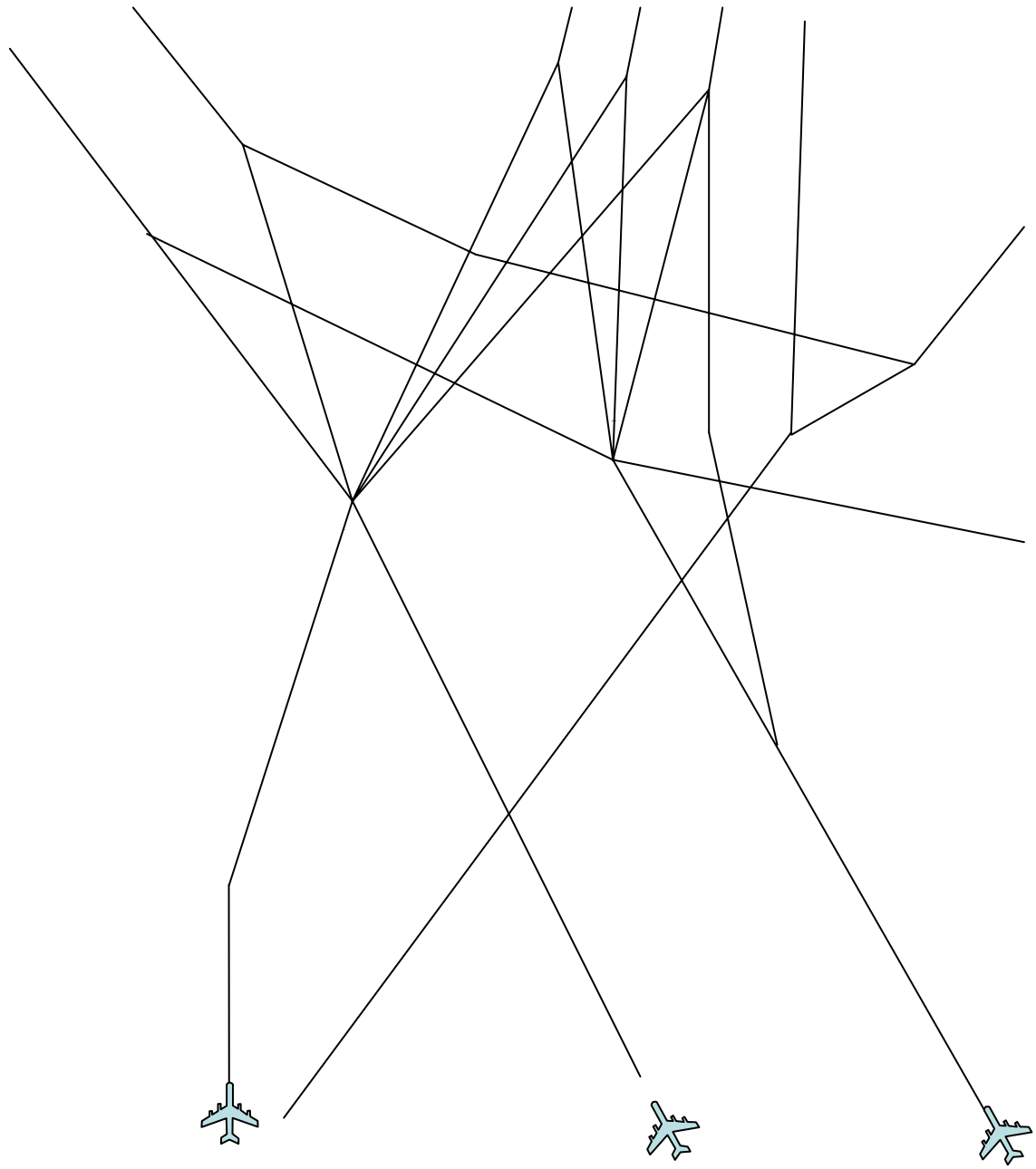
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- 2,5 millions aircraft over French air space in 2002
- Estimated increase: 3 - 5 % per year
- How to assume this increase with the same safety high level ?:
=> an assistance tool

ZOOM

AFFICHAGE

The radar screen

Conflict between two aircraft

Electronic strip

TOUS

430
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330 -
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RCH128V
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MANAK

RCH128V	TIOCH	DILRA	CGC	VELIN	SECHE
B742 474 GS	14:16	14:20	14:25 330	14:31	C2
KDOV LICZ					109
330 330 - 330					0

14:12

DEGEX

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KEPER

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DEVRO

AMB

NEV

NTS

PEPAX

VASON

KUSOS

RUXP

TIRAV

BIND

MDDSA

LCA

MOU

ATN

LAGOR

TUFAR

POI

ADABITUDRA

GUERE

THR

MADOT

ABSEN

DILRA

CGC

BOLGU

FOUCO

DIBAG

LMG

BEBIX

ADAKO

VALKU

ADEKA

ETREK

BDX

SAU

VELIN

POKET

PERIG

MAKOX

OLRAK

MEN

GONIM

BADAM

LERGA

LATAM

MTU

ENSAC

AGN

FISTO

MAJEL

TOU

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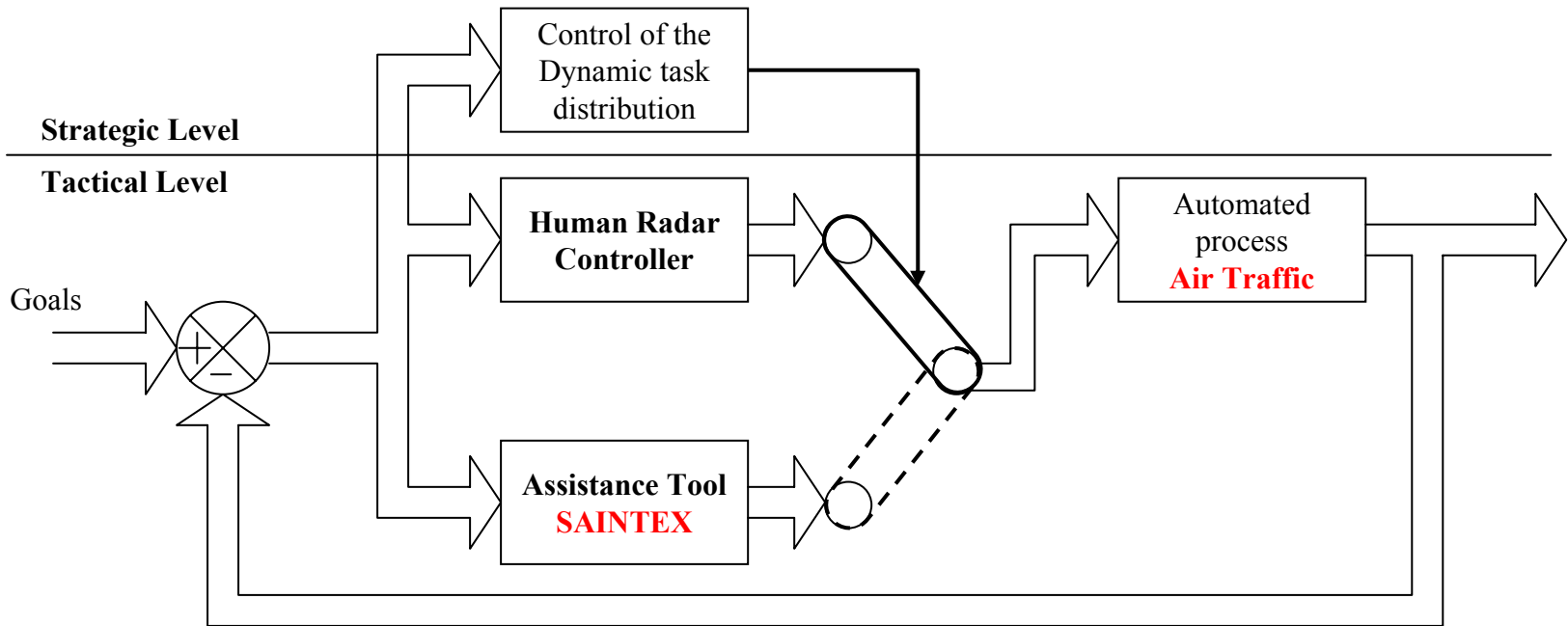
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ADAB



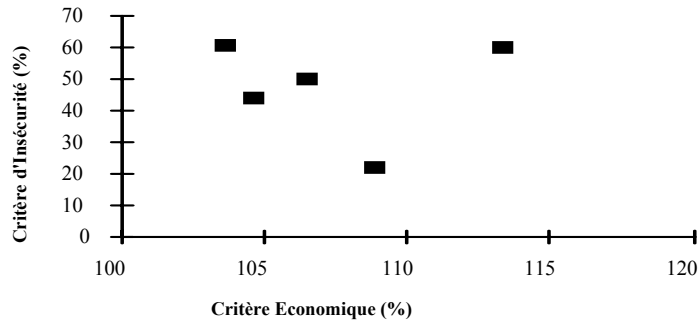
SPECTRA V1 & SPECTRA V2 Projects:

- Dynamic task distribution
- Autonomous Assistance Tool (problem detection, strategy, solution, command)

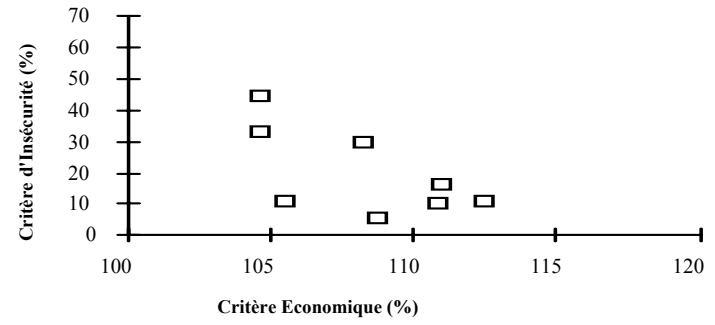
Hypotheses to test experimentally:

- Human Workload decreases ?
- Global Traffic performance increases ?

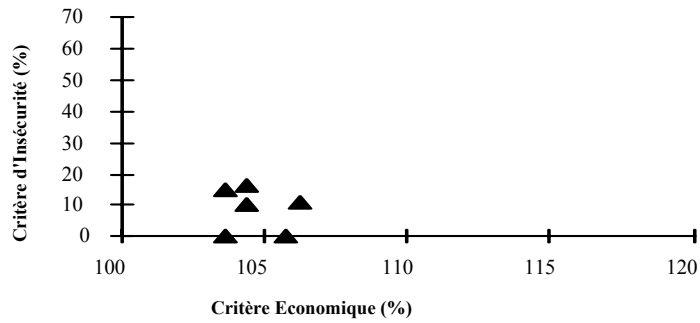
Stagiaires : Sans Aide



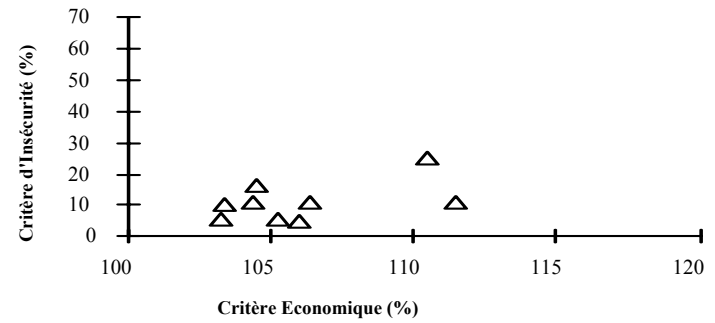
Certifiés : Sans Aide



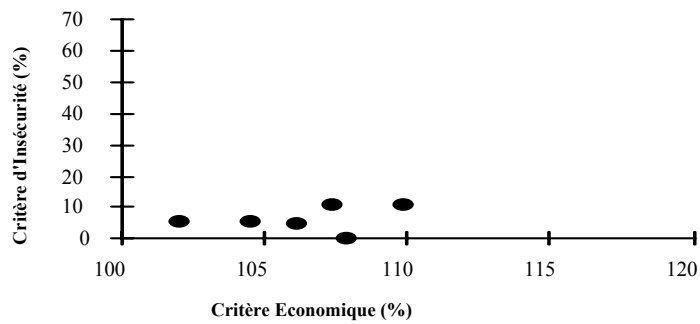
Stagiaires : Explicite



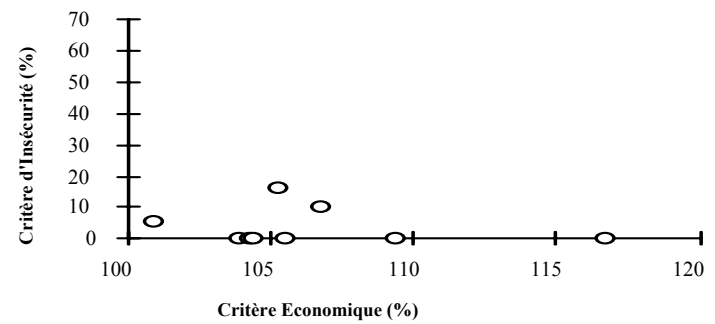
Certifiés : Explicite



Stagiaires : Implicite

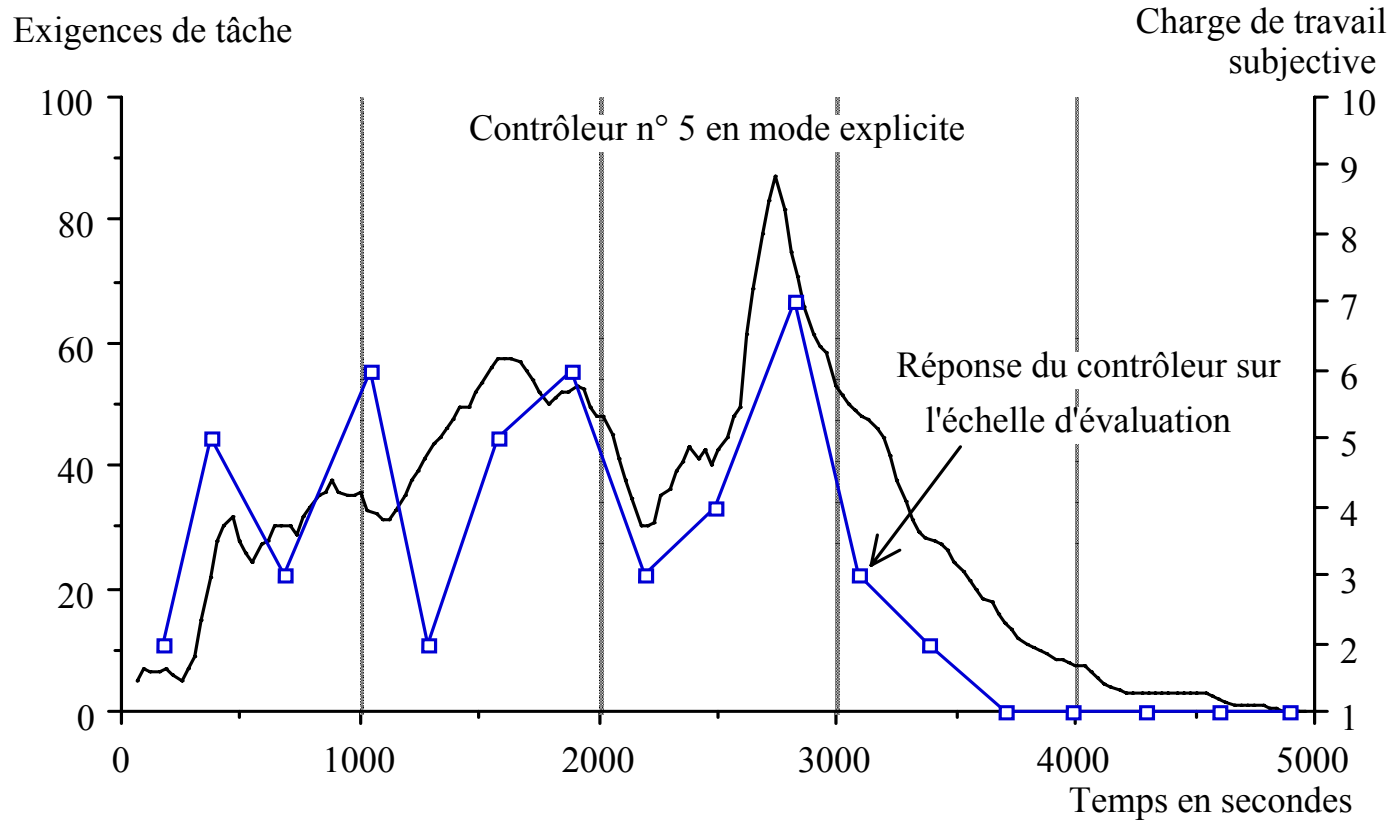


Certifiés : Implicite

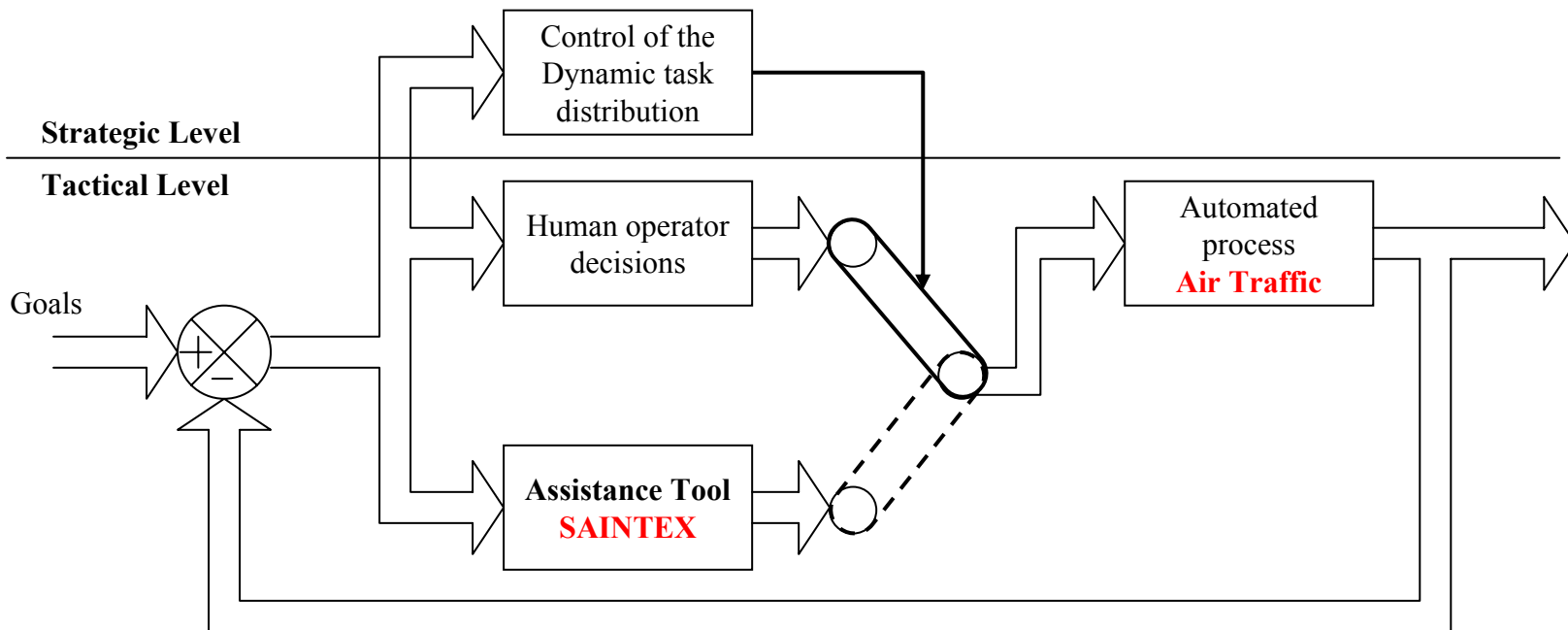


Global performance according to both controller expertise levels and the 3 control modes: without any assistance, explicit mode and implicit mode

Comparaison Exigences de tâches / Charge de travail subjective



Example of comparison between tasks demands and subjective WL along time for the controller no 5 in an experiment with SAINTEX in explicit mode



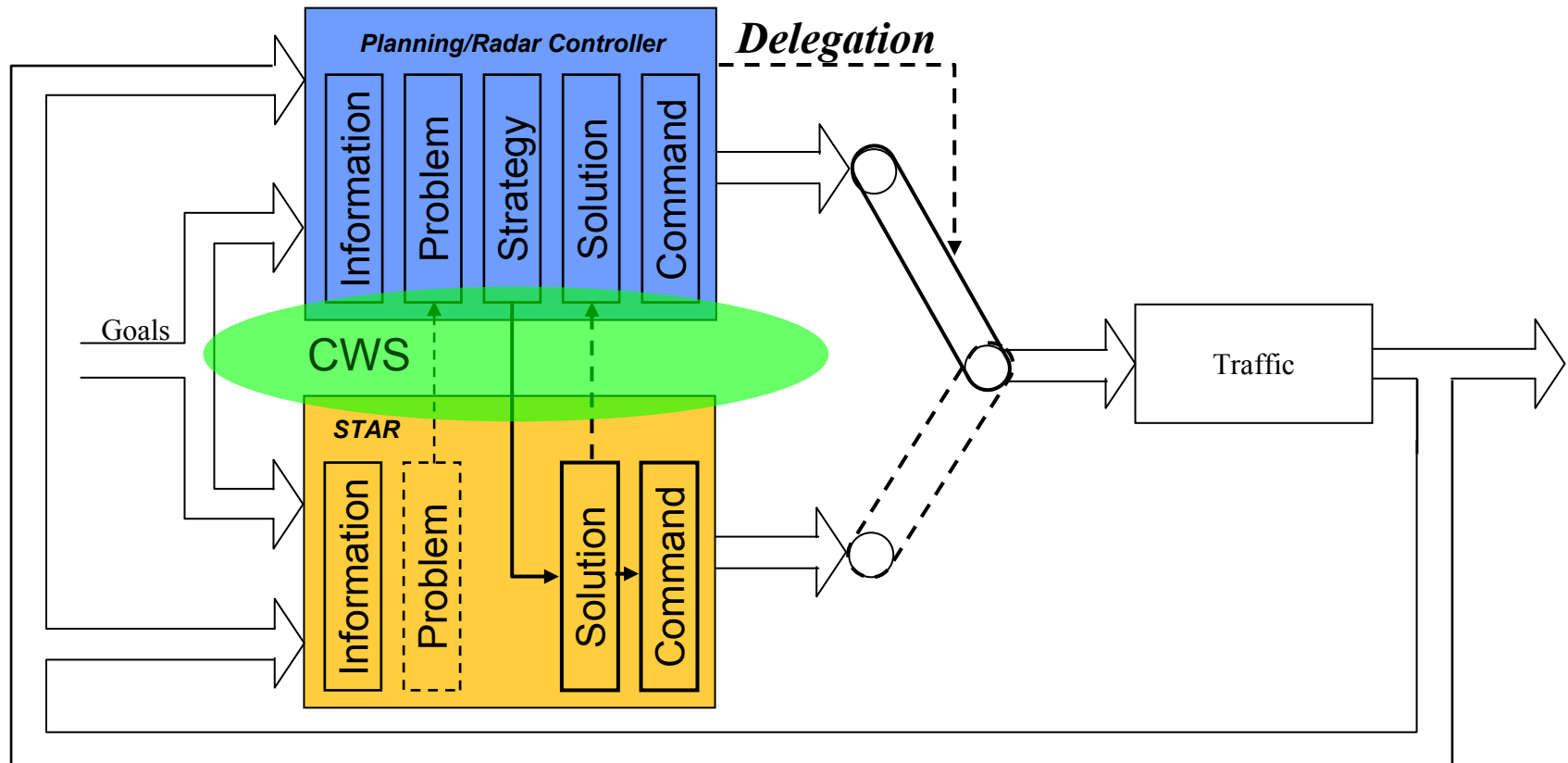
SPECTRA V1 & SPECTRA V2 Projects:

Results

- Dynamic task distribution
- Autonomous Assistance Tool SAINTEX (problem detection, strategy, solution, command)
- The hypotheses are verified: Human Workload decreases and global performances increase

But :

- Negative interferences between controllers and SAINTEX:
 - Problems in the definition and the allocation of the tasks
 - Divergence in the resolution strategies between the Human and SAINTEX
 - Organisational and juridical difficulties



AMANDA Project:

- Definition of a new **support tool called STAR** that integrates human strategies for calculating and implementing solutions
- Definition of a **Common Work Space CWS** that allows both agents (human and artificial) to share information and to negotiate

ZOOM

AFFICHAGE

The radar screen

Conflict between two aircraft

Electronic strip

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PPN

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MANAK

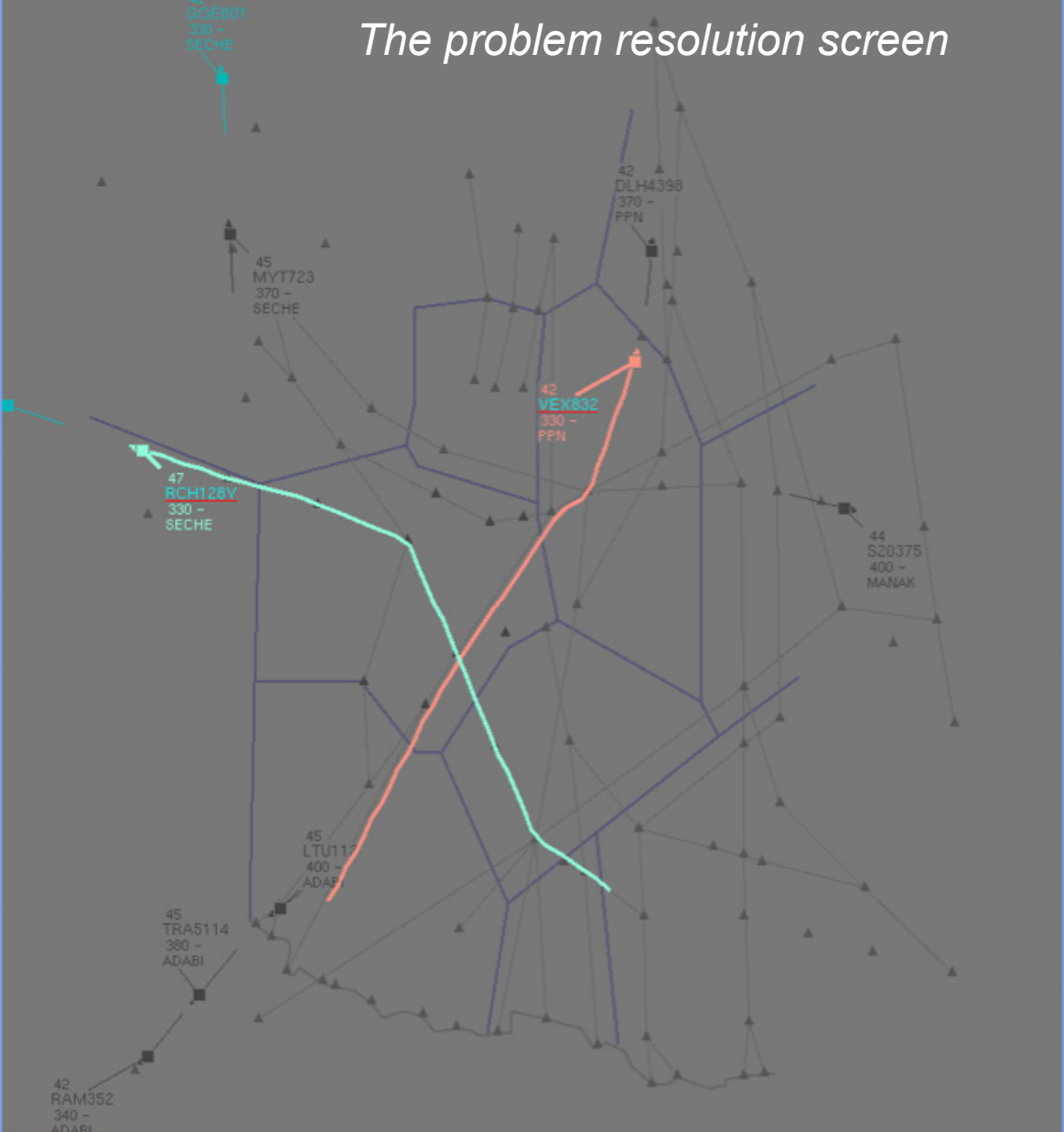
RCH128V	TIOCH	DILRA	CGC	VELIN	SECHE
B742 474 GS	14:16	14:20	14:25 330	14:31	C2
KDOV LICZ					109
330 330 - 330					0

14:12

The problem resolution screen

CFL
EFL
TFL

430	-5	0	+5
410	-10	10	+10
400	-15	20	+15
390	-20	30	+20
380	-25	40	+25
370	-30	50	+30
360	-35	60	+35
350	-40	70	+40
340	-45	80	+45
330	-50	90	+50
320	-55	100	+55
310	-60	110	+60
300	-65	120	+65
290	-70	130	+70
280	-75	140	+75
270	-80	150	+80
260	-85	160	+85
250	-90	170	+90
240	-95	180	+95
230	-100	190	+100
220	-105	200	+105
210	-110	210	+110
200	-115	220	+115
190	-120	230	+120
180	-125	240	+125
170	-130	250	+130
160	-135	260	+135
150	-140	270	+140
140	-145	280	+145
130	-150	290	+150
120	-155	300	+155
110	-160	310	+160
100	-165	320	+165
90	-170	330	+170
80	-175	340	+175
	-180	350	+180



COULEUR CLUSTER

SUPPRIMER CLUSTER

DISSOCIER

ORDRE DIFFERE

SORTIR

RCH128Y	
VEX832	

VEX832 RCH128Y 6 MN PB

TAUX VITESSE

AJOUTER VOL	AJOUTER ORDRE D.	AJOUTER DIRECTIVE	SIMULATION	VALIDER
IGNORER VOL	SUPPRIMER O. D.	SUPPRIMER DIRECTIVE	DELEGATION	ANNULER
SUPPRIMER VOL	MODIFIER ORDRE D.	MODIFIER DIRECTIVE	REPRENDRE	SORTIR

CFL
EFL
TFL

430	-5	0	+5
410	-10	10	+10
400	-15	20	+15
390	-20	30	+20
380	-25	40	+25
370	-30	50	+30
360	-35	60	+35
350	-40	70	+40
340	-45	80	+45
330	-50	90	+50
320	-55	100	+55
310	-60	110	+60
300	-65	120	+65
290	-70	130	+70
280	-75	140	+75
270	-80	150	+80
260	-85	160	+85
250	-90	170	+90
240	-95	180	+95
230	-100	190	+100
220	-105	200	+105
210	-110	210	+110
200	-115	220	+115
190	-120	230	+120
180	-125	240	+125
170	-130	250	+130
160	-135	260	+135
150	-140	270	+140
140	-145	280	+145
130	-150	290	+150
120	-155	300	+155
110	-160	310	+160
100	-165	320	+165
90	-170	330	+170
80	-175	340	+175
	-180	350	+180

The problem resolution screen

2 commands for the aircraft deviation

New trajectory
calculated by STAR

Aircraft
delegated
Initial trajectory

Strategy built by the controller

COULEUR CLUSTER

SUPPRIMER CLUSTER

DISSOCIER

ORDRE DIFFERE

SORTIR

RCH128Y

VEX832

VEX832 RCH128Y 9 MN OK

RCH128Y PASSER DERRIERE VEX832 OK

TAUX

VITESSE

AJOUTER VOL

AJOUTER ORDRE D.

AJOUTER DIRECTIVE

SIMULATION

VALIDER

IGNORER VOL

SUPPRIMER O. D.

SUPPRIMER DIRECTIVE

DELEGATION

ANNULER

SUPPRIMER VOL

MODIFIER ORDRE D.

MODIFIER DIRECTIVE

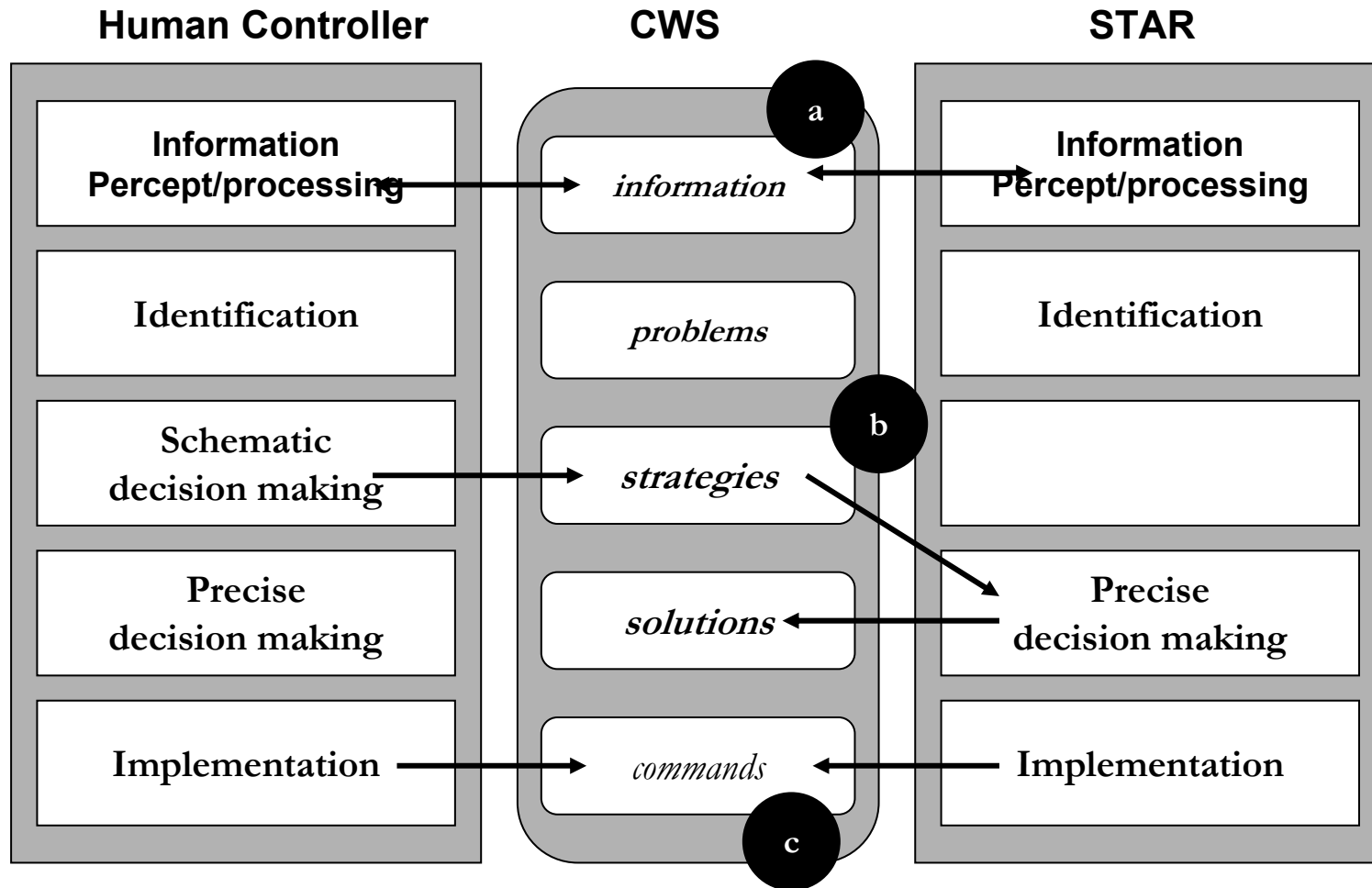
REPRENDRE

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AMANDA V2

L A M I H

Human-Machine Cooperation: multiple forms



a: debative

b: integrative

c: augmentative

Conclusion

1. The results of these experiments:

- show an increase of performance when Human cooperates with the machine
- stress the need to allow error recovery means to achieve performance
- stress the importance of the COFOR

2. Further studies are needed:

- for modelling and implementing cooperation in action with applications for instance to car driving tasks
- for discovering the task parameters which contribute or refrain cooperation: workload, trust and self confidence, motivation

Thank you for your attention

IFAC TC 4.5 Human Machine Systems

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Analysis Design and Evaluation of Human Machine Systems

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patrick.millot@univ-valenciennes.fr