GDR Groupement de recherche
MACS Modélisation, Analyse et Conduite des Systèmes dynamiques

JUNEAU
JUmeau Numérique pour un sErvice d'Accueil des Urgences

Digital twin for human-based organisation
An example on Emergency Department

Laboratoire Décision et Information Pour les Systèmes de Production

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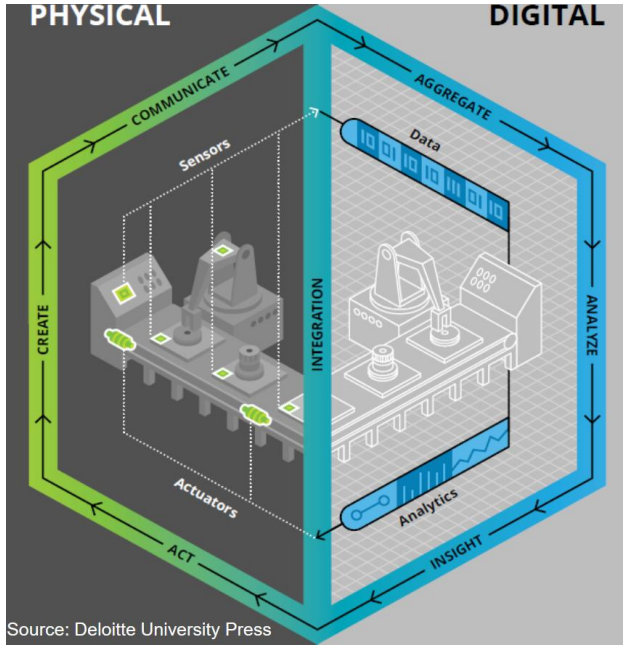
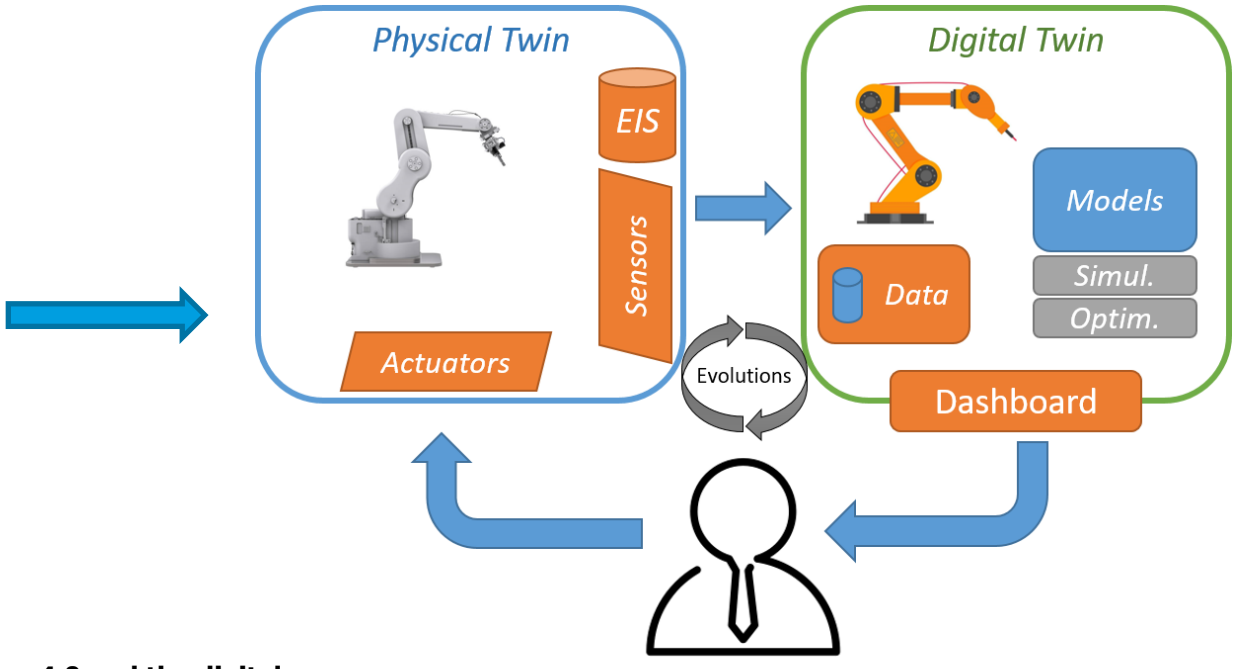
Agenda

- DT and Human
- JUNEAU project overview
- Patient model
- ED organisation simulation model
- Model evolution
- Conclusions & Perspectives

DT and Human

- Digital Twin definition for today :
  - Digital Twinning defines the **physical entity**, the **virtual entity** which is the digital mirror model in high fidelity, and the **connection** that ties the two parts together. It forms the loop from the physical world to the virtual world, and back to the physical world again, with an **Human in the loop**. As such, a Digital Twin is a provider of services.





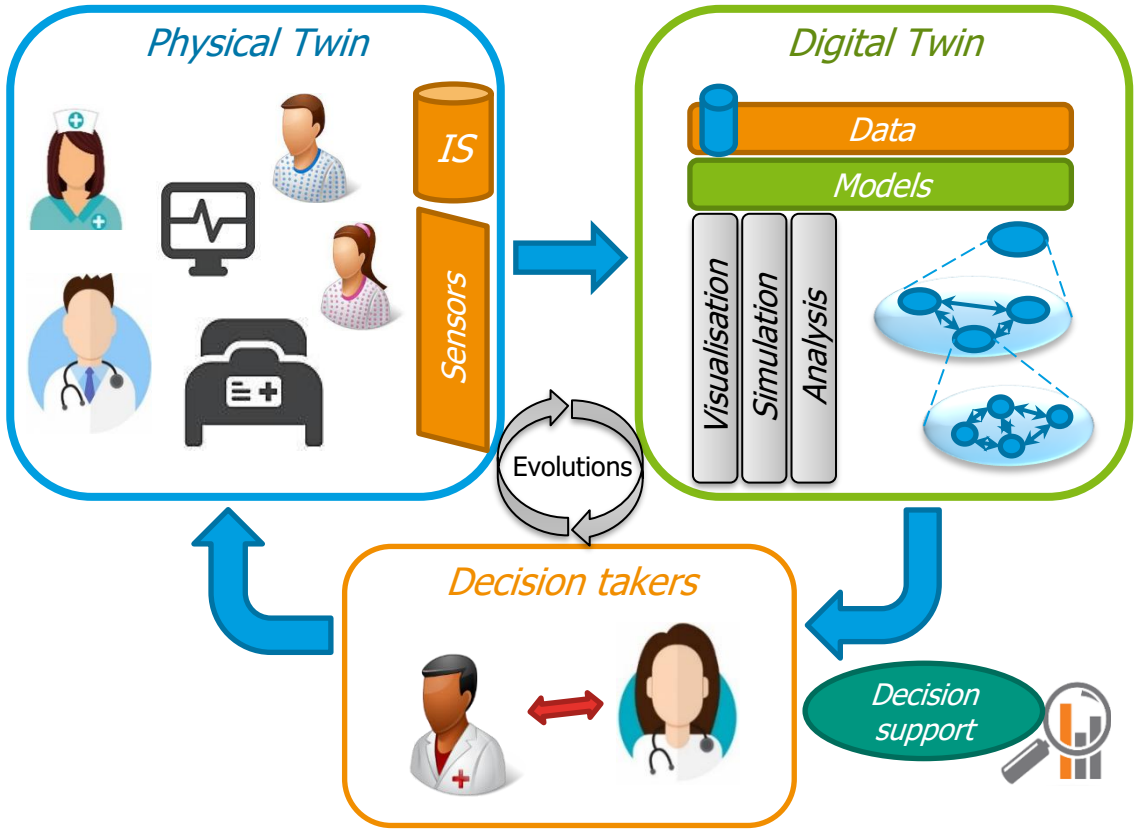
DT
=
Decision-support
data-based
twinned

A. Parrott and L. Warshaw (2017) "**Industry 4.0 and the digital twin manufacturing meets its match**", Deloitte University Press

DT and Human

- Position of an human in the DT ?
  - Decision-maker,
  - agent,
  - supervisor of the DT,
  - etc.

- Human-Simulation



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JUNEAU project

JUmeau Numérique pour un sErvice d'Accueil des Urgences

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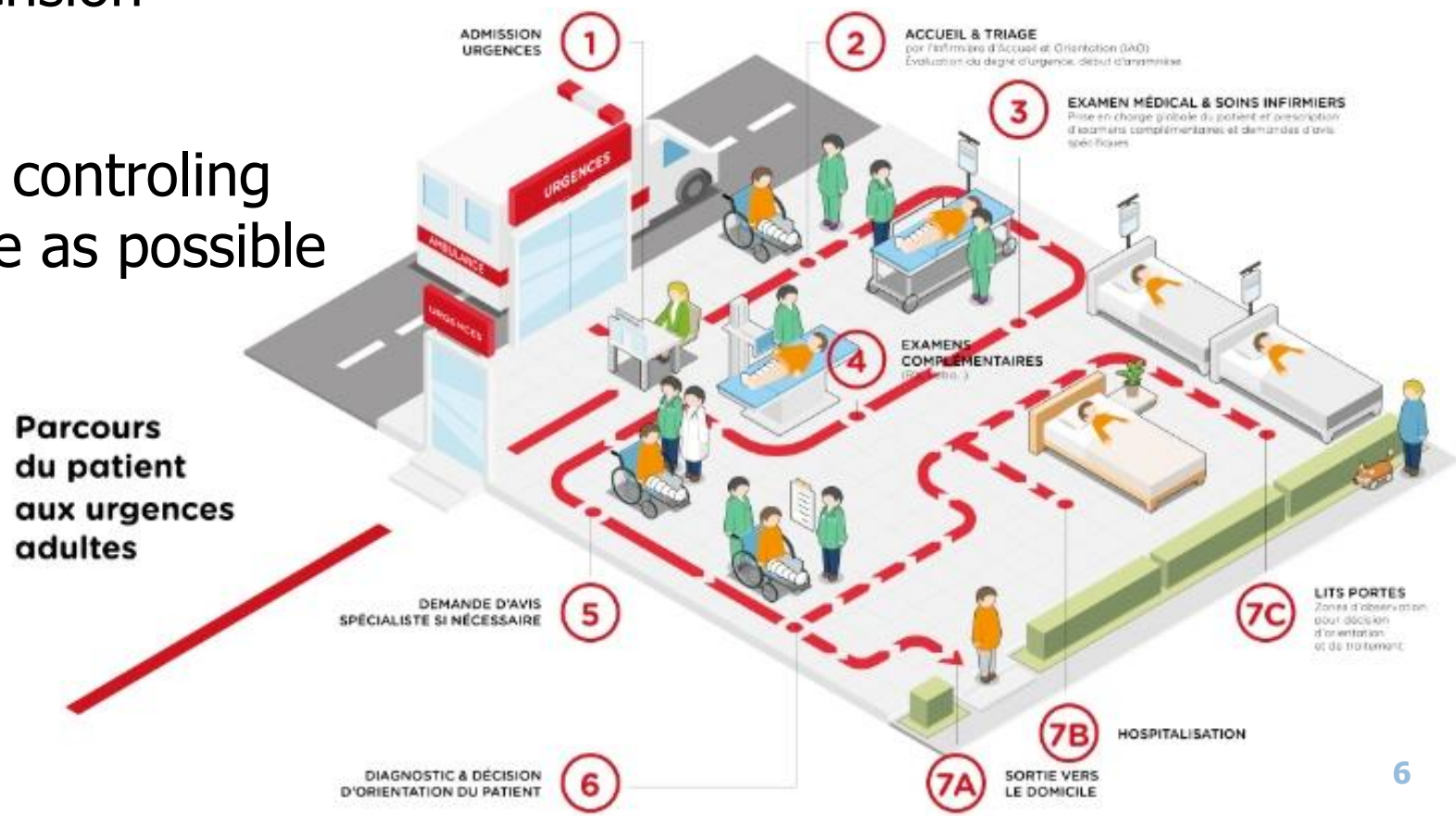
JUNEAU

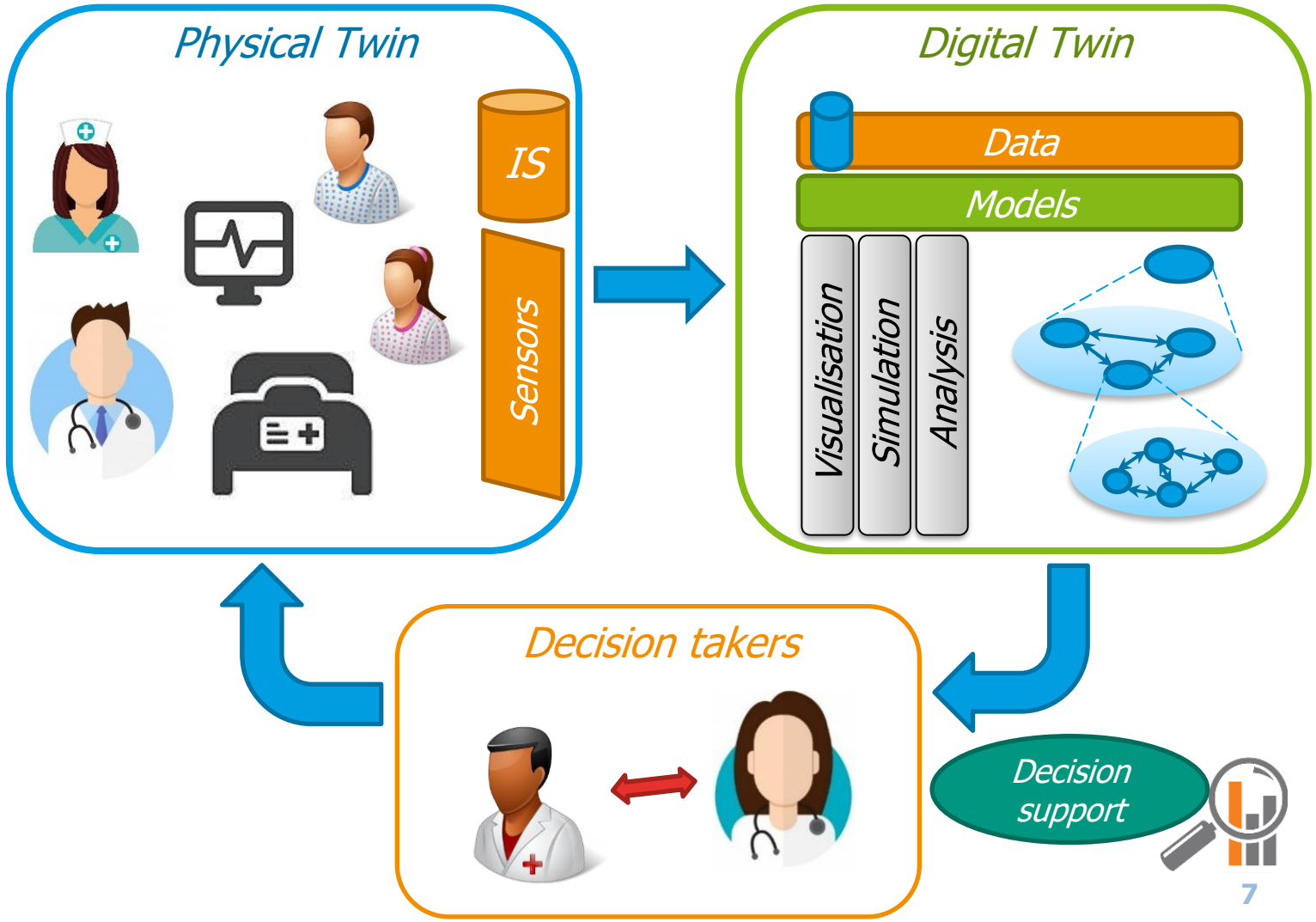
JUmeau Numérique pour
un sErvice d'Accueil des Urgences

- Complex system, often in tension
  - Largely human-based
  - Strongly uncertain
- => needs for supervising & controling the patient pathway as close as possible



JUNEAU project

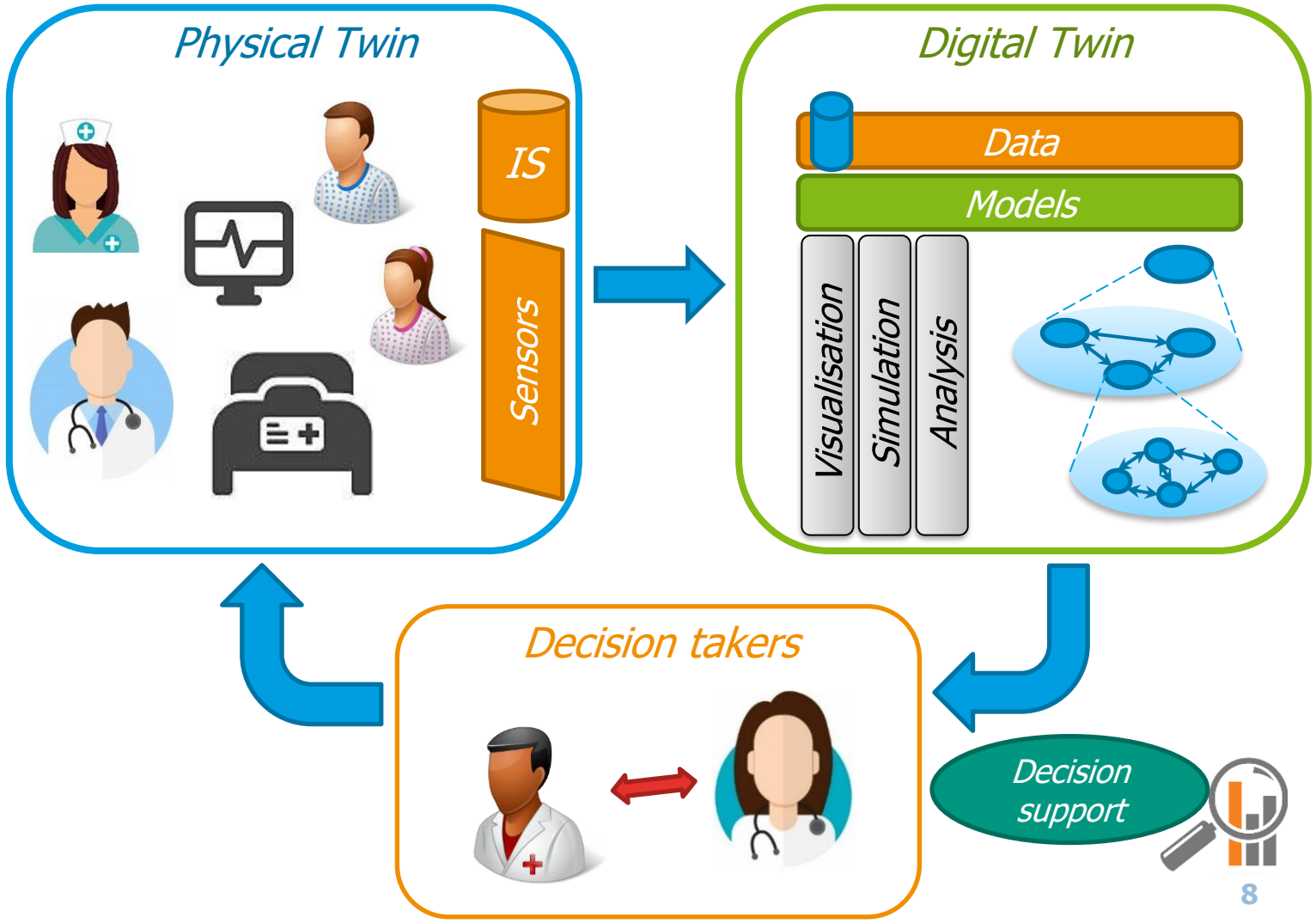
- Our proposition: *to control "passage time for patients' emergencies" indicator with a DT for ED*
  - to trace the data necessary to visualise the behaviour of the service in near real time
  - to predict and anticipate its behaviour, by coupling simulation and optimisation



G. Bouleux et al. **Requirements for a Digital Twin for an Emergency Department**, SOHOMA'22

JUNEAU project

- Some requirements
  - Different human decision makers in the loop
  - Integration & interoperability with the hospital information system
  - Hybrid control (combination of centralised and distributed one)
  - As non-invasive as possible
  - Should evolve in a dynamic, uncertain and evolving context



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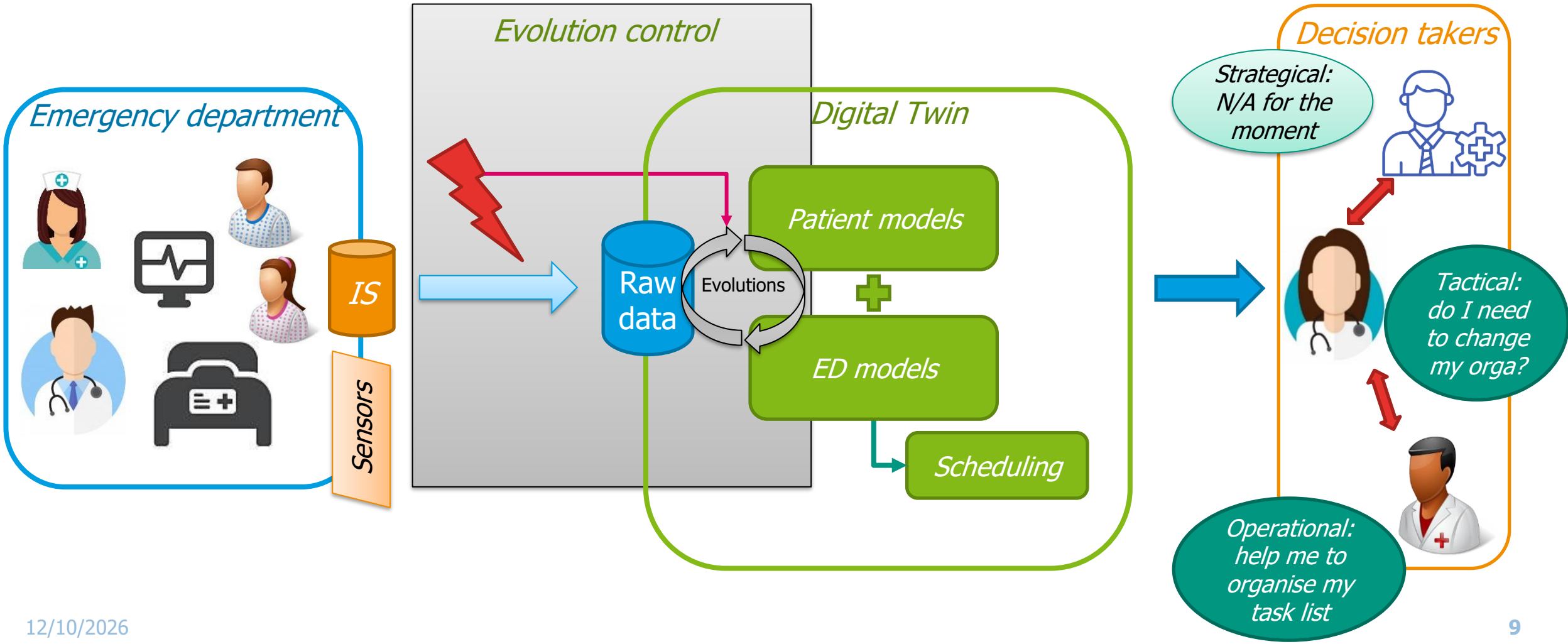
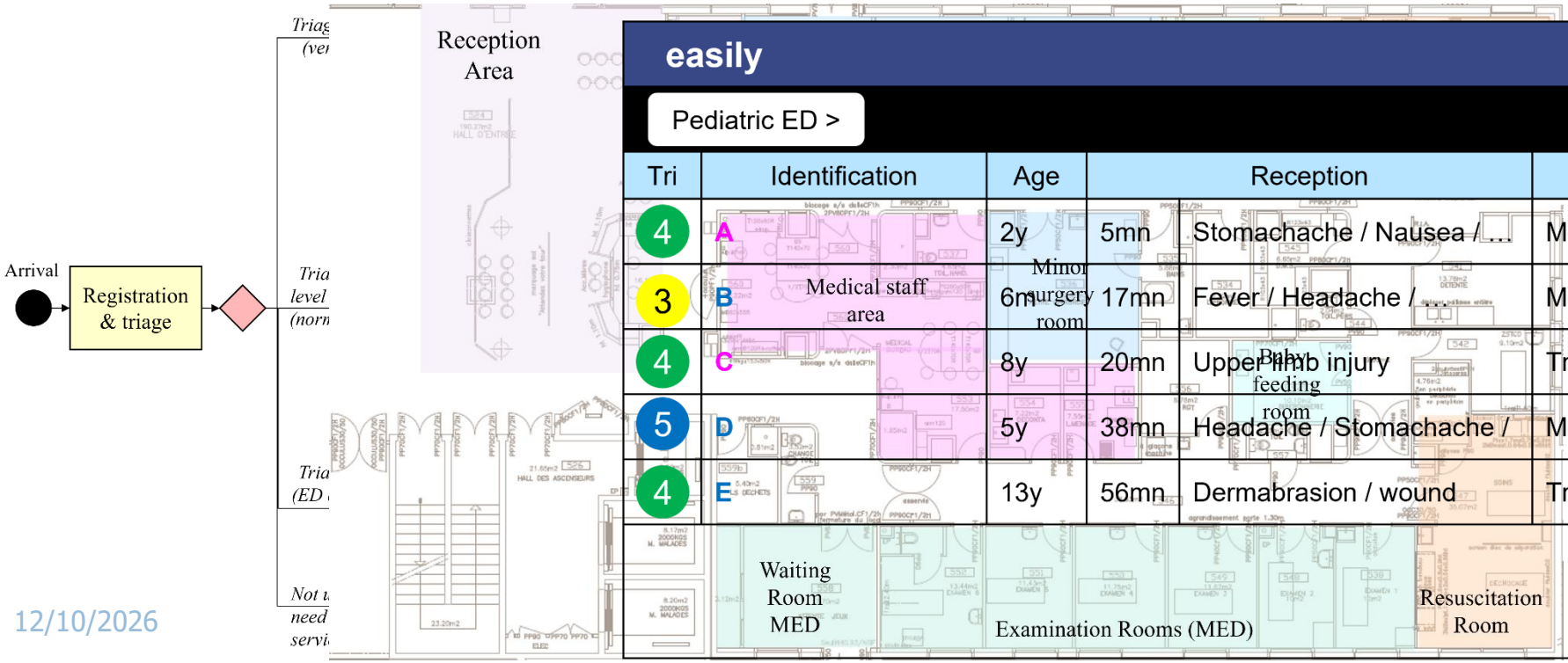
JUNEAU project



JUNEAU project

Paediatric ED of Saint-Etienne hospital

- Patients : children from 3 months to 15 years
- Two sectors : Trauma (CHI) and Medecine (MED), with dedicated resources
- Human resources: nurses (with Triage nurse), externs, interns and seniors
- Dedicated information system already in usage



easily

Pediatric ED >

Tri	Identification	Age	Reception		Sector	Care	Location
4	A	2y	5mn	Stomachache / Nausea / …	Medical	AD	Hall
3	B	6m	17mn	Fever / Headache / …	Medical	MF JL	Examination R3
4	C	8y	20mn	Upper limb injury	Trauma	ST CM	Surgery R1
5	D	5y	38mn	Headache / Stomachache /	Medical	MF JL	Examination R5
4	E	13y	56mn	Dermabrasion / wound	Trauma	ST CM	Surgery R2

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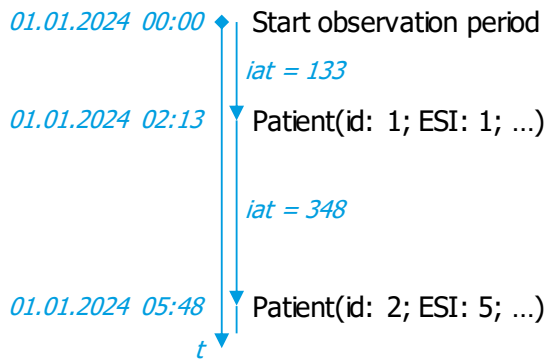
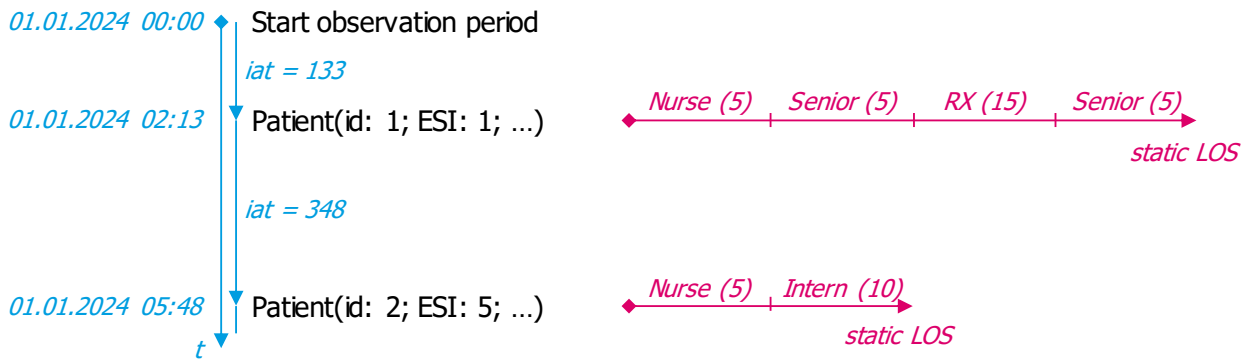
Patient model

- Describing patient population by a model of arrivals “arrival stream”
  - Inter-arrival Time: Time between patient and its predecessor
  - Sequence of patients: Defined through unique ID and attributes



Patient model

- Describing patient population by their sequence of activities “pathways”
  - Pathway: Sequence of treatments to undergo
  - Treatment duration: Duration of each treatment



Patient model
Patient arrivals

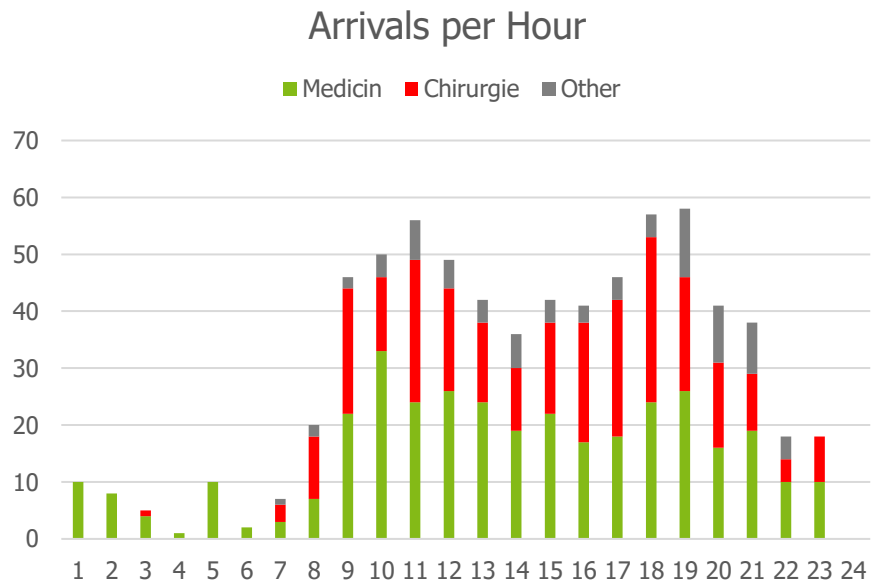
Available information:

- Historic patient arrivals

case_id	iat [sec]	gravity	sector	sortie	UHCD
430539	17.03.2023 20:38	G4	Méd	Domicile	1
430539	17.03.2023 21:30	G4	Méd	Domicile	0
430539	17.03.2023 21:37	G5	Méd	Domicile	0
430539	17.03.2023 23:08	G5	Méd	Domicile	0
430539	17.03.2023 23:15	G4	Chi	Domicile	0
430539	18.03.2023 03:40	G4	Méd	Domicile	1
430539	18.03.2023 08:14	G4	Méd	Domicile	1
430539	18.03.2023 08:50	G3	Méd	Domicile	0

Transfer to simulation

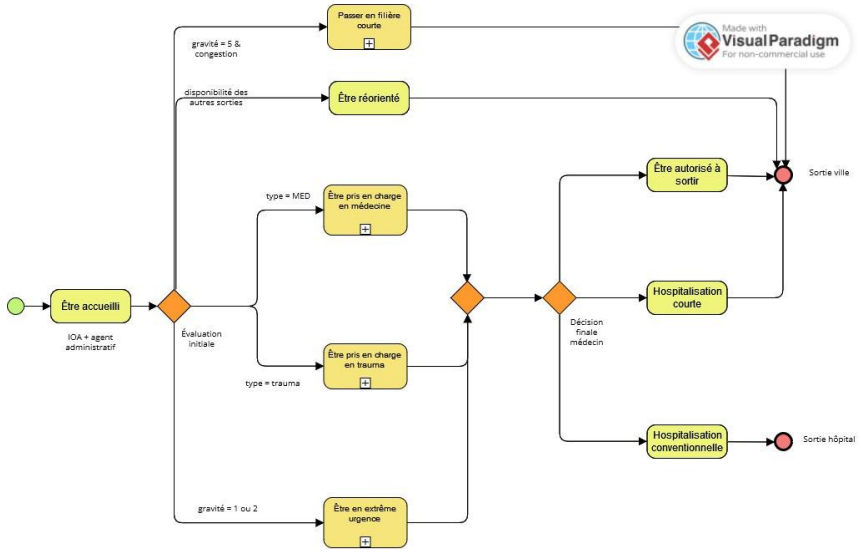
- Provide a (stochastic) model of the arrival stream



Patient model
Patient pathway

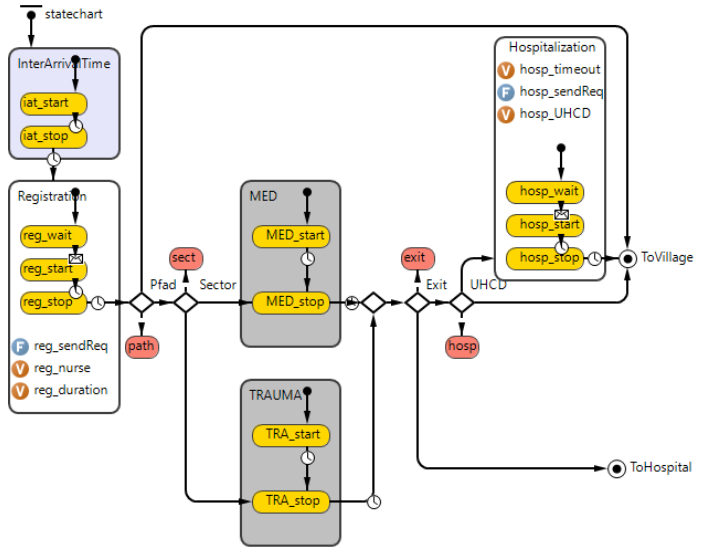
Available information:

- Historical pathway data (8000 patients)
- BPMN with patient journeys (events, activities, information flow)



Transfer to simulation

- Provide an activity-based model of patient pathways



Patient model
General conceptual framework

1. Historic data

Population of historic patients for situation (t)



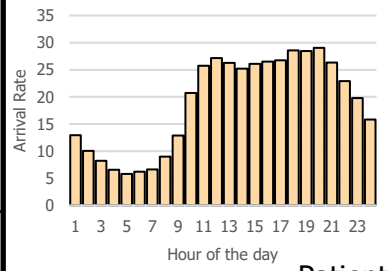
Extract the model of the historic patients

Extract each **situation**, e.g.:
- Arrival/Departure of patients
- Begin/End of a treatment

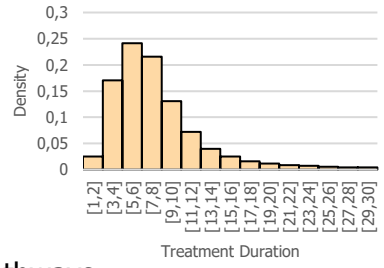
2. Data-Science (Prediction)

Patient Model

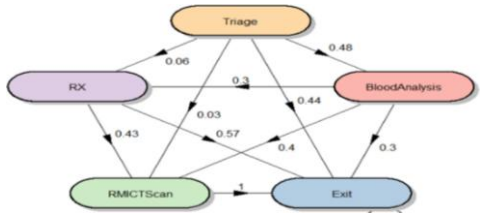
Arrival Stream
(Hourly Arrival Rates)



Treatment Duration
(Monte Carlo Simulation)



Patient pathways
(Markov Chains)



Initial Situation
- Patients that already in the ED
- Pathways that already on the way

Generate 20 patient populations per situation

Replicate each situation in ED

3. Simulation (measure queues)

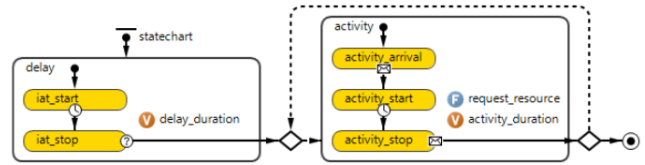
Generic "Job-Shop"-Simulator

Simuler les flux patients au sein des Urgences grâce un modèle à base d'agents piloté par les données

Michael Schlecht [1,2], Jessica Florencia [1], Thierry Moyaux [1], Lorraine Trilling [1], Vincent Cheutet [1], Sarah Devidal [2], Aymeric Cantais [2], Guillaume Bouleux [1]

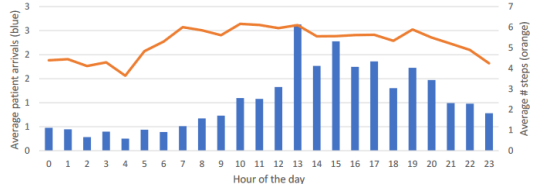
[1] INSA Lyon, Université Lumière Lyon 2, Université Claude Bernard Lyon 1, Université Jean Monnet Saint-Etienne, DISP UR4570, Villeurbanne, michael.schlecht@insa-lyon.fr

[2] CHU de Saint-Etienne, Av. Albert Raimond, 42270 Saint-Priest-en-Jarez, Sarah.Devidal@chu-st-etienne.fr



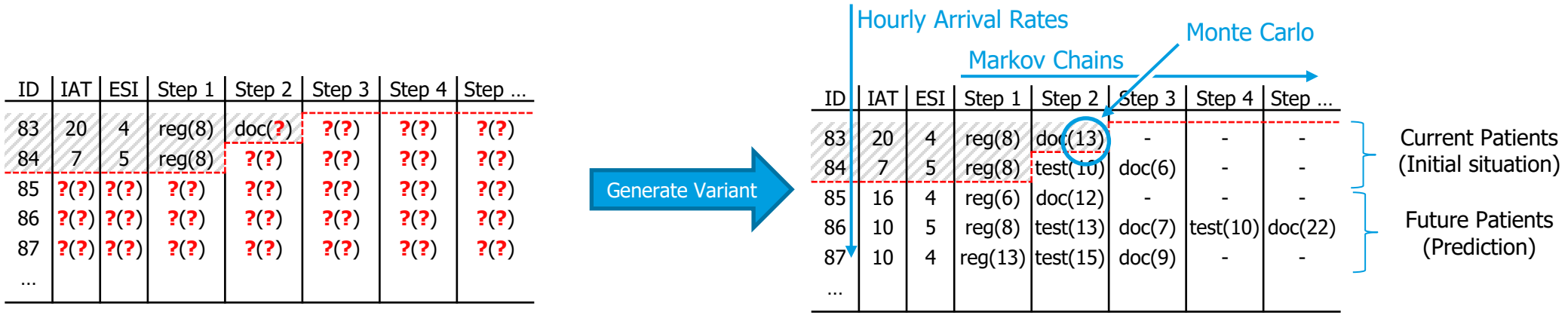
Simulate 20 populations for each situation in ED

Prediction of waiting lines



Patient model

- Predict patient population:



- Methods of prediction
  - Patient Arrivals: Hourly Arrival Rates
  - Patient Pathways: 1st order Markov Chains
  - Treatment Durations: Monte Carlo Simulation

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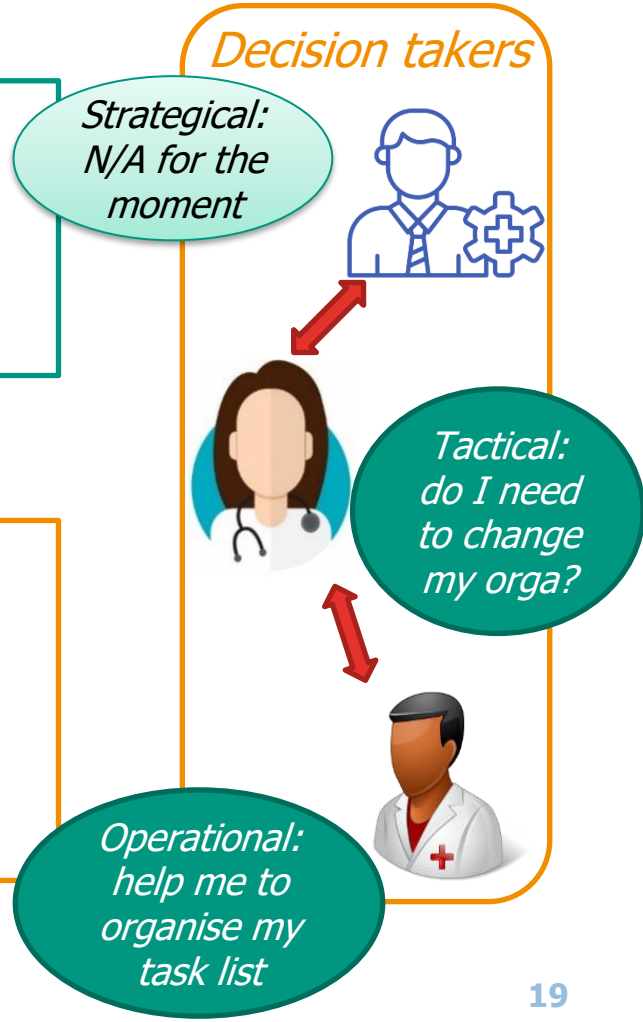
ED simulation model
Research Objectives and Question

Research Objective

- develop dynamic resource scheduling model to effectively manage patient flow in ED

Research Questions

- What approach can be used to dynamically schedule treatment tasks to resources in ED?
- What indicators used to evaluate the decision model in ED?



ED simulation model

Methods: Three-stage Dynamic Resource Scheduling



ED simulation model
Initial study

Decision-making structure

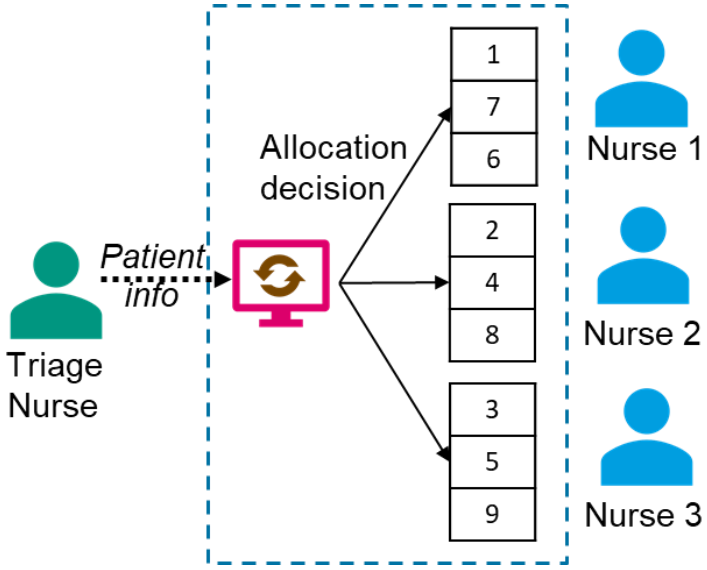
Centralised ← compromise → **Decentralised**

Optimal global decision — Best performance
lack of reactivity — Large computation time

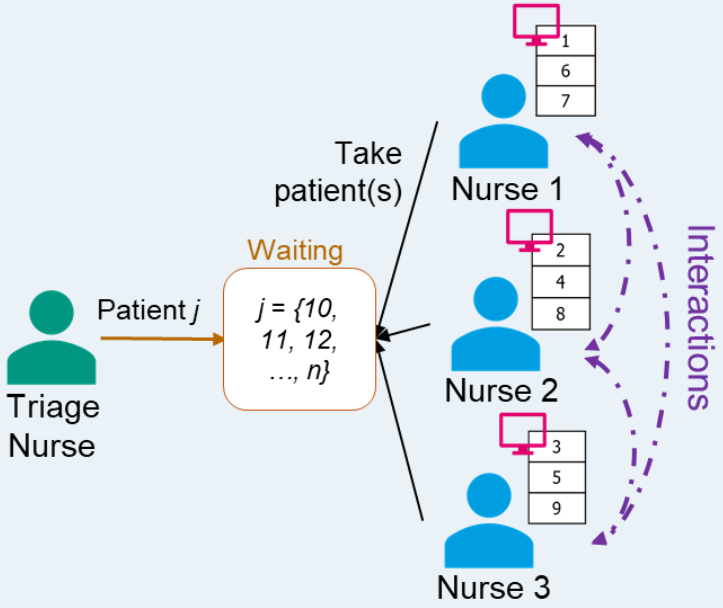
Small computation time
good performance

Reactive local decision — Smallest comp. time
lack of global view — Worse performance

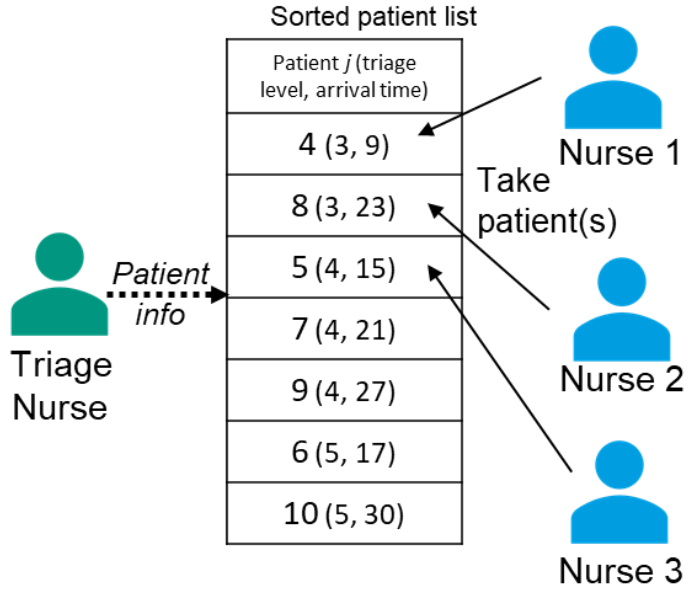
Global scheduling MILP



Multi-agent + local scheduling MILP



Triage-based FCFS



Initial study of different simple resource scheduling decision making structure

ED simulation model

Methods: Three-stage Dynamic Resource Scheduling

Initial study

Decentralised organisation exploration

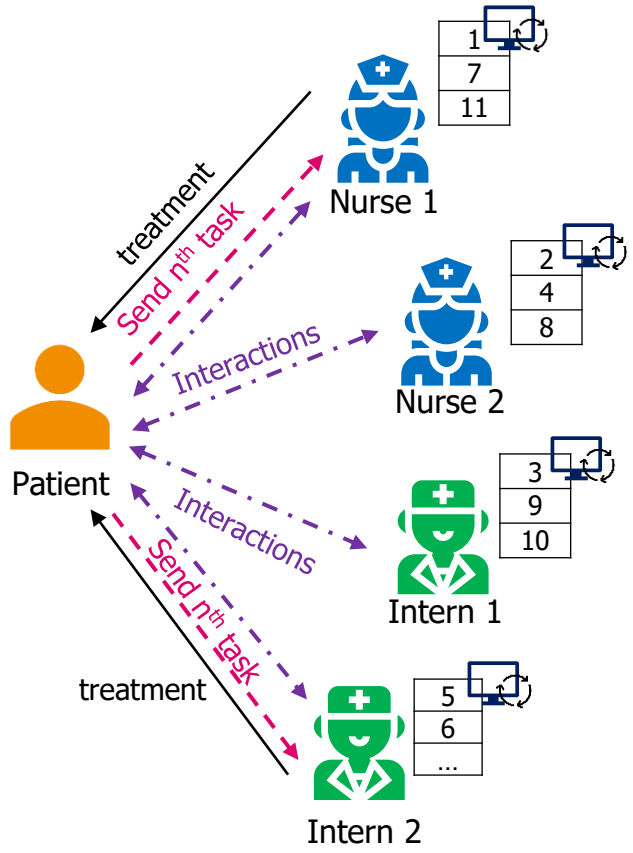


- Compare:
  - Centralised
  - **Decentralised**
  - Triage-based FCFS
- Case: Each resource (nurse) does **1 treatment task** for each patient
- **Decentralised organisation** compromises centralised and FCFS in terms of solution quality and computation time

ED simulation model

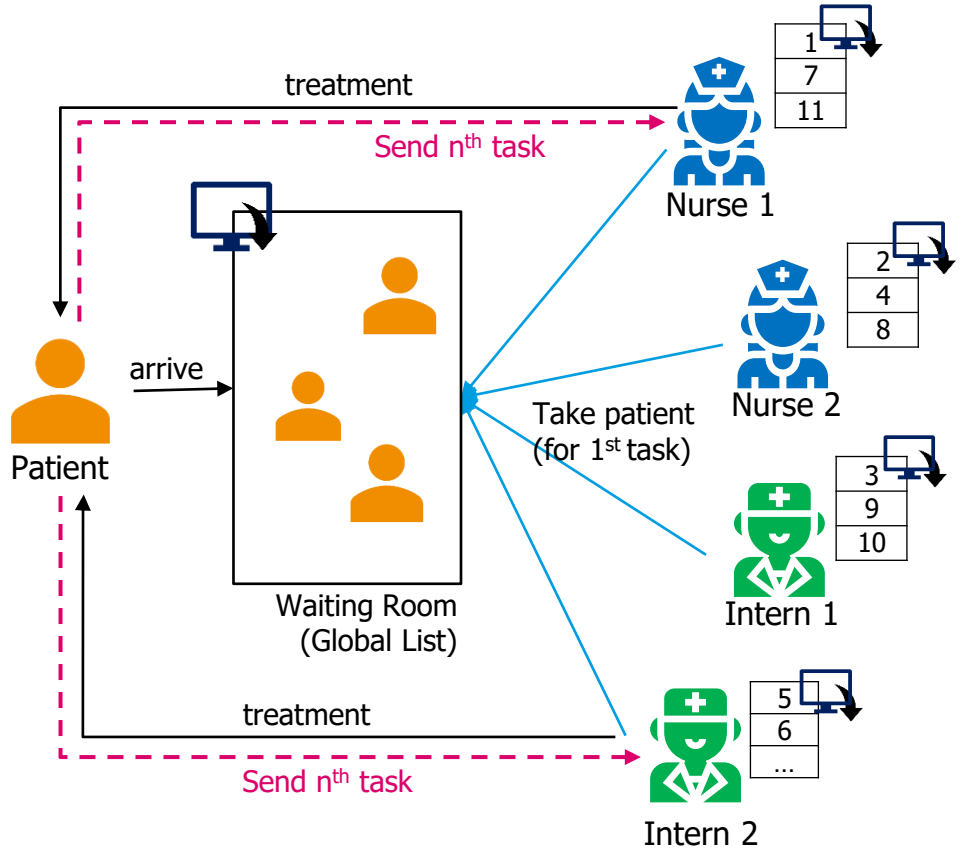
Resource Scheduling in ED: Model Overview

Agent-based Job Shop



Task assignment: auction led by patient
Task sequencing: local sequencing algorithms

Agent-based Priority Queue



Task assignment: triage-based FCFS + first patient rules
Task sequencing: priority queues

ED simulation model

Methods: Three-stage Dynamic Resource Scheduling

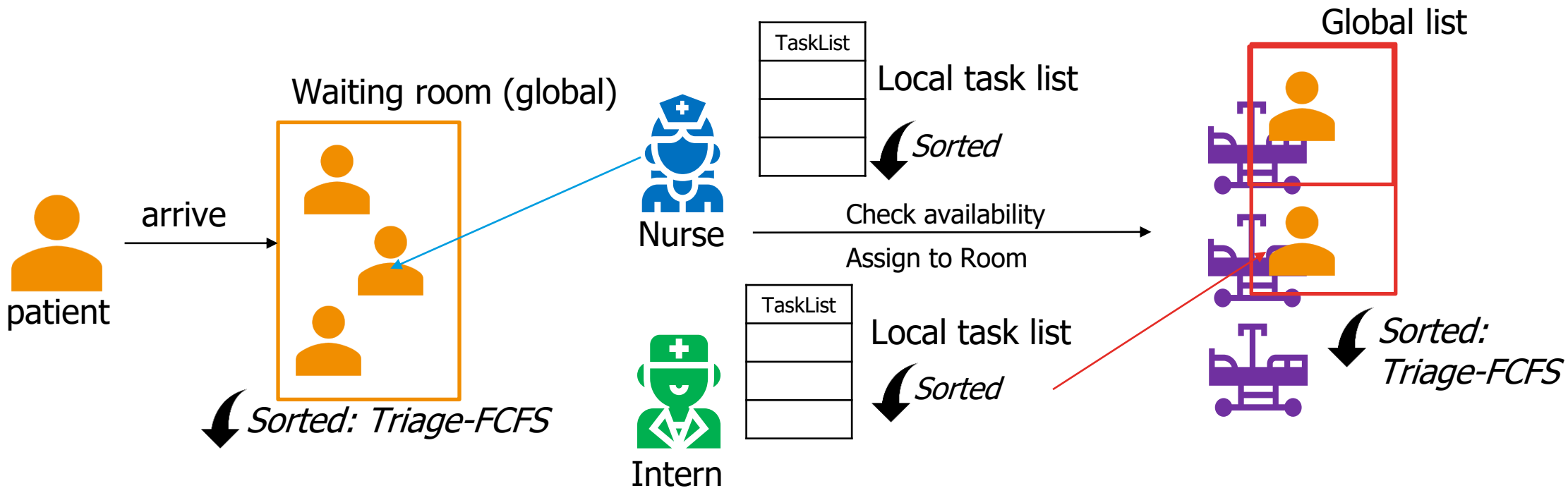
Initial study → Decentralised organisation exploration → ED model





- Compare:
  - Agent-based Job Shop
  - Agent-based Priority Queue
- Case: Each resource (nurse, physician) performs **multi-stage treatments** for each patient
- **Agent-based Priority Queue** is an effective method.

ED simulation model
Overview



Assumption: The patient does not leave the room until all treatment is finished

ED simulation model
Local Sequencing Rules

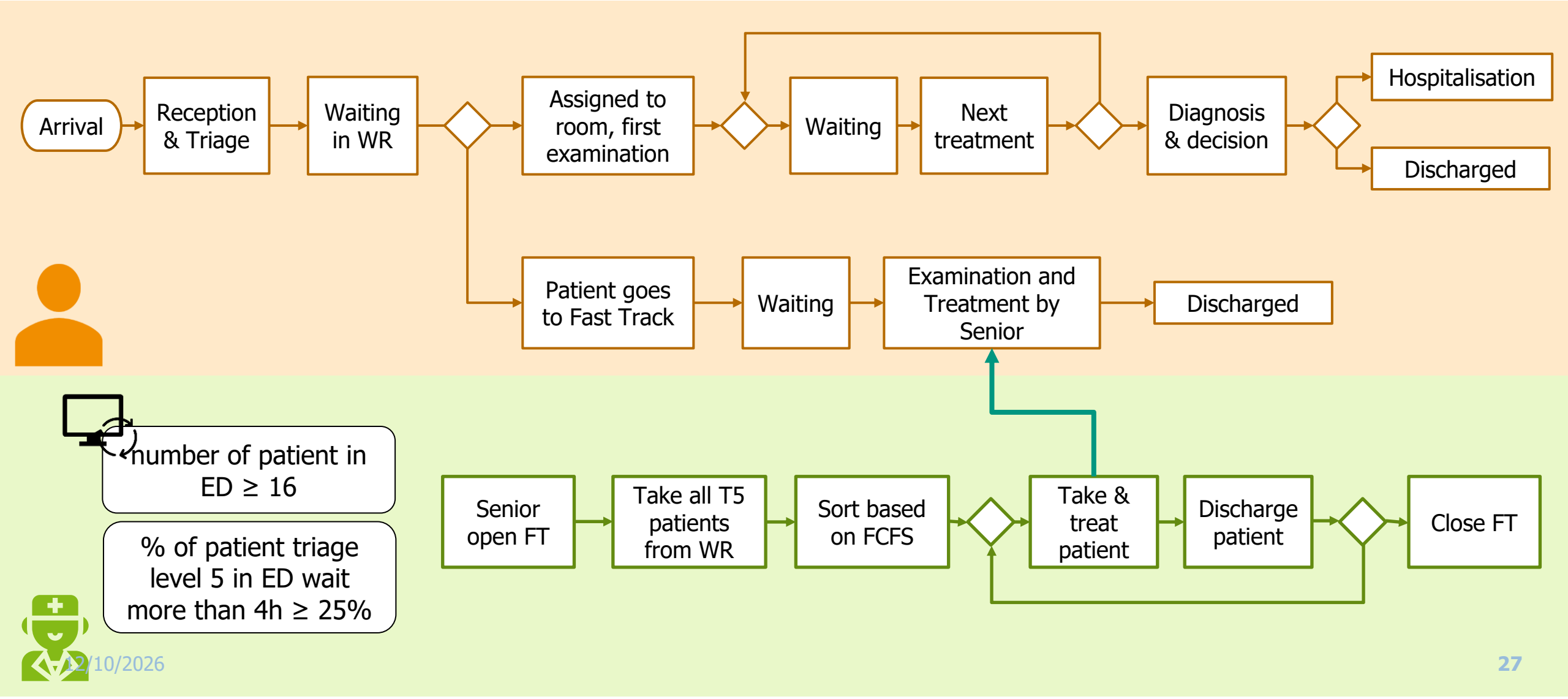
- **1S-Triage**: Prioritize patient that wait in WR to deal with quck patient visit
- **nS-Triage**: Prioritize treatment of patient who is inside room (to free the room quickly)
- **Triage-1S**: Prioritize high severity patient, emphasizing to take patient to first treatment as soon as possible
- **Triage-nS**: Prioritize high severity patient, emphasizing to finish the Surrent treatment as soon as possible (to free the room quickly)

Discipline	Sorting Order									
	1	2	3	4	5	6	7	…	J-1	J
1S-Triage	1S-T1	1S-T2	1S-T3	1S-T4	1S-T5	2S-T1	2S-T2	…	nS-T4	nS-T5
nS-Triage	nS-T1	nS-T2	nS-T3	nS-T4	nS-T5	(n-1)S-T1	(n-1)S-T3	…	1S-T4	1S-T5
Triage-1S	1S-T1	2S-T1	3S-T1	4S-T1	5S-T1	6S-T1	7S-T1	…	(n-1)S-T5	nS-T5
Triage-nS	nS-T1	(n-1)S-T1	(n-2)S-T1	(n-3)S-T1	(n-4)S-T1	(n-5)S-T1	(n-6)S-T1	…	2S-T5	1S-T5

S = treatment steps/stages?
T = triage level
J = number of sorting order possible

*3S-T5: 3rd consultation, triage level 5

ED simulation model
Fast Track (FT) Decision



ED simulation model

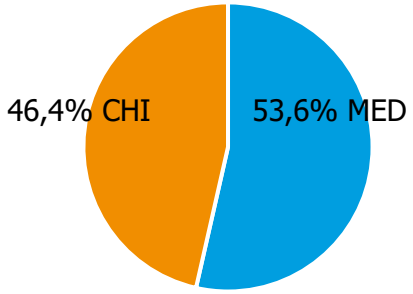
ED model data and settings

Normal Period

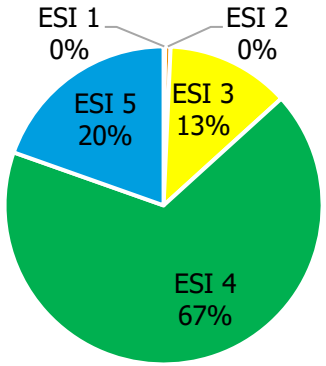
Patients

2-weeks data (June 2023): 1266 patients

Sector



Triage level



Resources

MED

5 Nurses | 7 Interns | 4 Externs | 4 Senior | 6 Boxes

CHI

3 Nurses | 6 Interns | 2 Senior | 4 Boxes

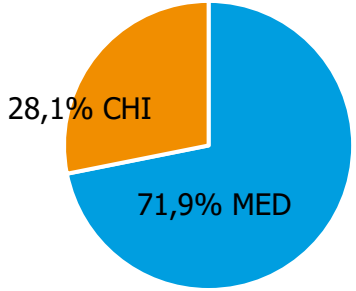
Radiology

Epidemic Period

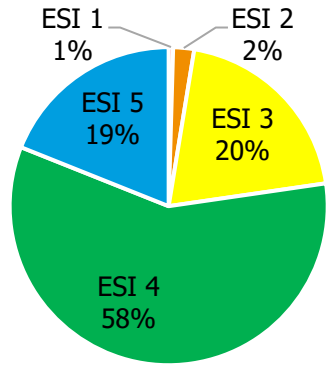
Patients

2-weeks data (December 2023): 1546 patients

Sector



Triage level



Resources

MED

5 Nurses | 7 Interns | 4 Externs | 4 Senior | 6 Boxes

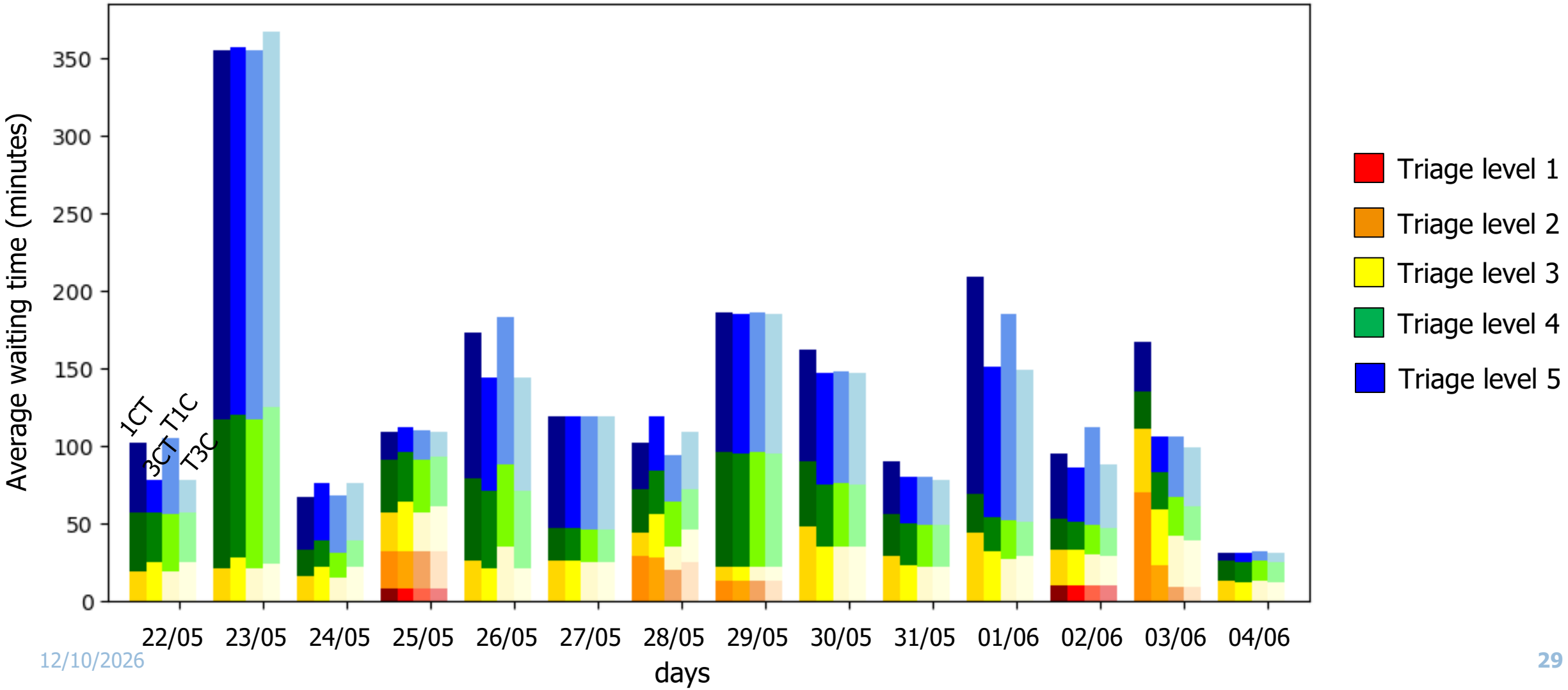
CHI

3 Nurses | 6 Interns | 4 Externs | 2 Senior | 4 Boxes

Radiology

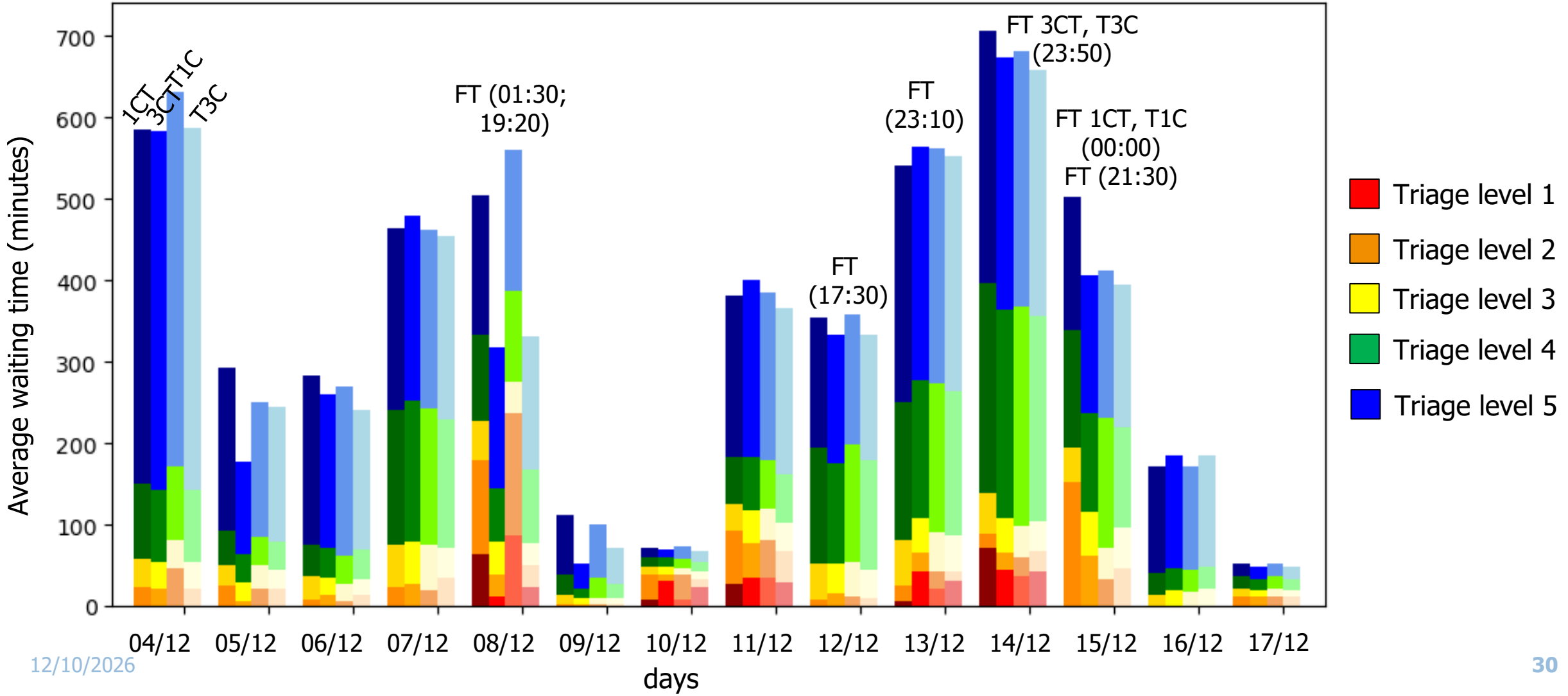
ED simulation model

Result (Normal): Average Waiting Time (daily)



ED simulation model

Result (Epidemic): Average Waiting Time (daily)



ED simulation model

Summary of Results: Waiting Time

Data	PQ	Total WT	Waiting Time ESI 1				Waiting Time ESI 2				Waiting Time ESI 3				Waiting Time ESI 4				Waiting Time ESI 5			
			Total	Mean	Std	Max	Total	Mean	Std	Max	Total	Mean	Std	Max	Total	Mean	Std	Max	Total	Mean	Std	Max
Normal (May-June)	1CT	52995	18	9	1,414	10	195	27,86	32,22	77	3972	24,98	30,65	188	32465	38,19	62,02	442	16345	65,9	128,19	1009
	3CT	49654	18	9	1,414	10	144	20,57	14,52	47	3946	24,82	26,22	188	31101	36,59	60,713	442	14445	58,2	124,91	1007
	T1C	52730	18	9	1,414	10	105	15	12,38	33	3453	21,72	23,57	188	32335	38,04	62,445	442	16819	67,8	128,59	1009
	T3C	50041	18	9	1,414	10	121	17,29	15,55	46	3626	22,81	24,95	188	31431	36,98	62,516	442	14845	59,9	125,9	1020
Epidemic (Dec)	1CT	181624	202	28,86	29,96	71	895	27,12	36,83	152	11864	38,15	36,83	254	101021	112	158,11	716	67642	231	264,65	1273
	3CT	168768	200	28,57	17,41	44	611	18,52	18,99	62	10829	34,82	30,90	177	93162	103,3	152,17	605	63966	218	261,68	1249
	T1C	184188	220	31,43	28,77	87	820	24,85	29,45	149	10890	35,02	33,05	236	104254	115,6	165,28	616	68004	232	268,71	1305
	T3C	170959	180	25,71	15,63	44	665	20,15	21,98	78	9855	31,69	27,21	146	95068	105,4	152,25	603	65191	222	261,61	1255

- In both condition, 3CT provides the best total waiting time, while 1CT gives the worst total waiting time. The strategy to free up bed (3CT) works well in a ED with bottleneck of beds
- In normal condition, T1C works best for higher urgency and worst for lower acuity. 3CT works best for lower acuity.
- In epidemic condition, T3C works the very good for higher urgency, and 3CT works the best for lower urgency.
- **Most stable strategy: T3C**

ED simulation model

Methods: Three-stage Dynamic Resource Scheduling



- ED model with Agent-based Priority Queue (PQ)
- Case: Each resource (nurse, physician, radiology staff) **from 2 sectors** performs **multi-stage treatments** for each patient **in a room**
- Integrate Fast Track (FT) decision
- Current result: no PQ rules that work the best (have the best indicator) in every situation

PhD thesis of **Jessica FLORENCIA**

Ensuring dynamic organizational performance in an agent-based organization – Application to an ED

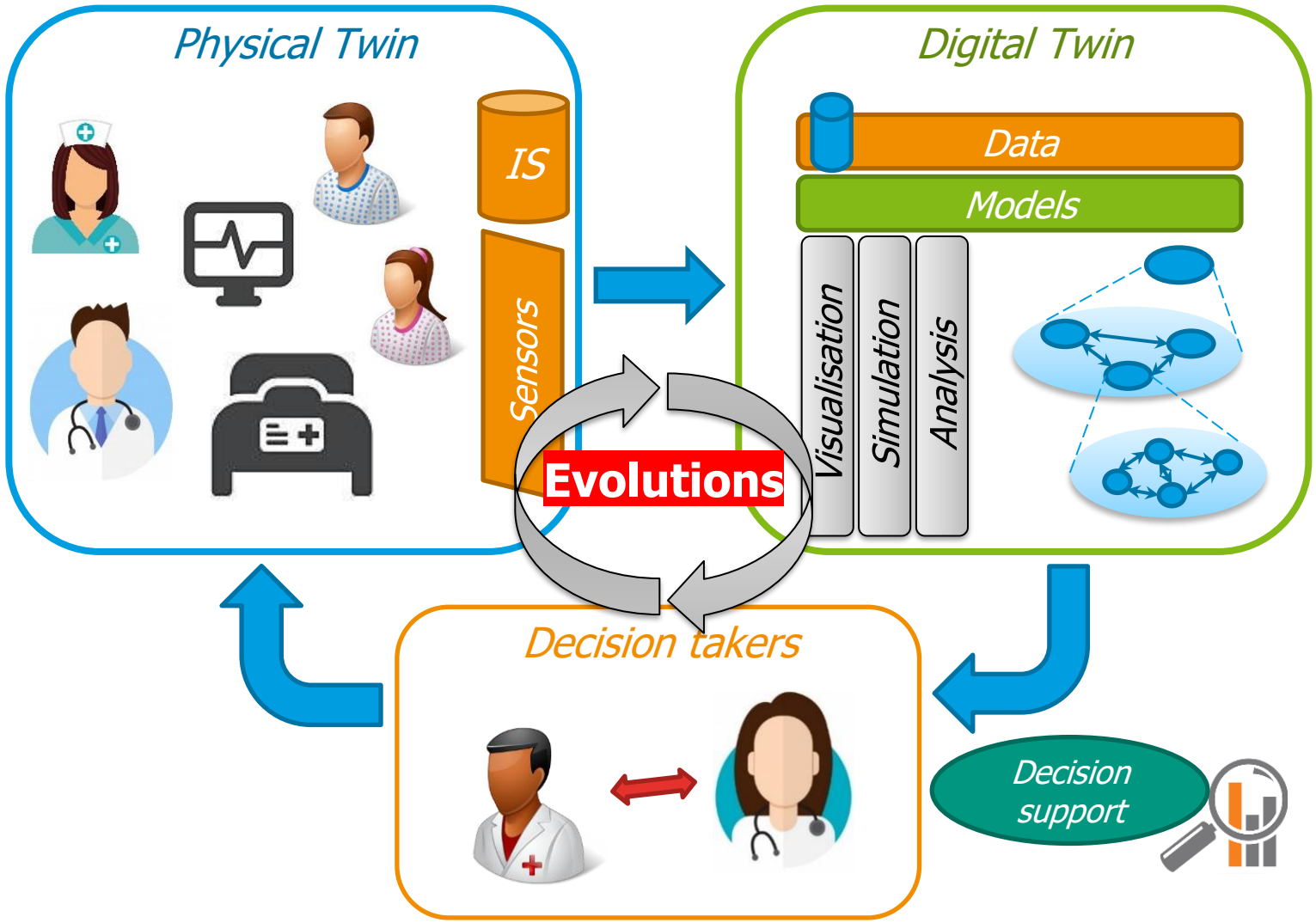
https://www.youtube.com/watch?v=SuCPE5bKQo4&list=PLFteQZhzdYWArPVex84ae-udlDAmuBnFA&index=3&pp=iAQBsAgC

Laboratoire
Décision et Information
Pour les Systèmes de Production

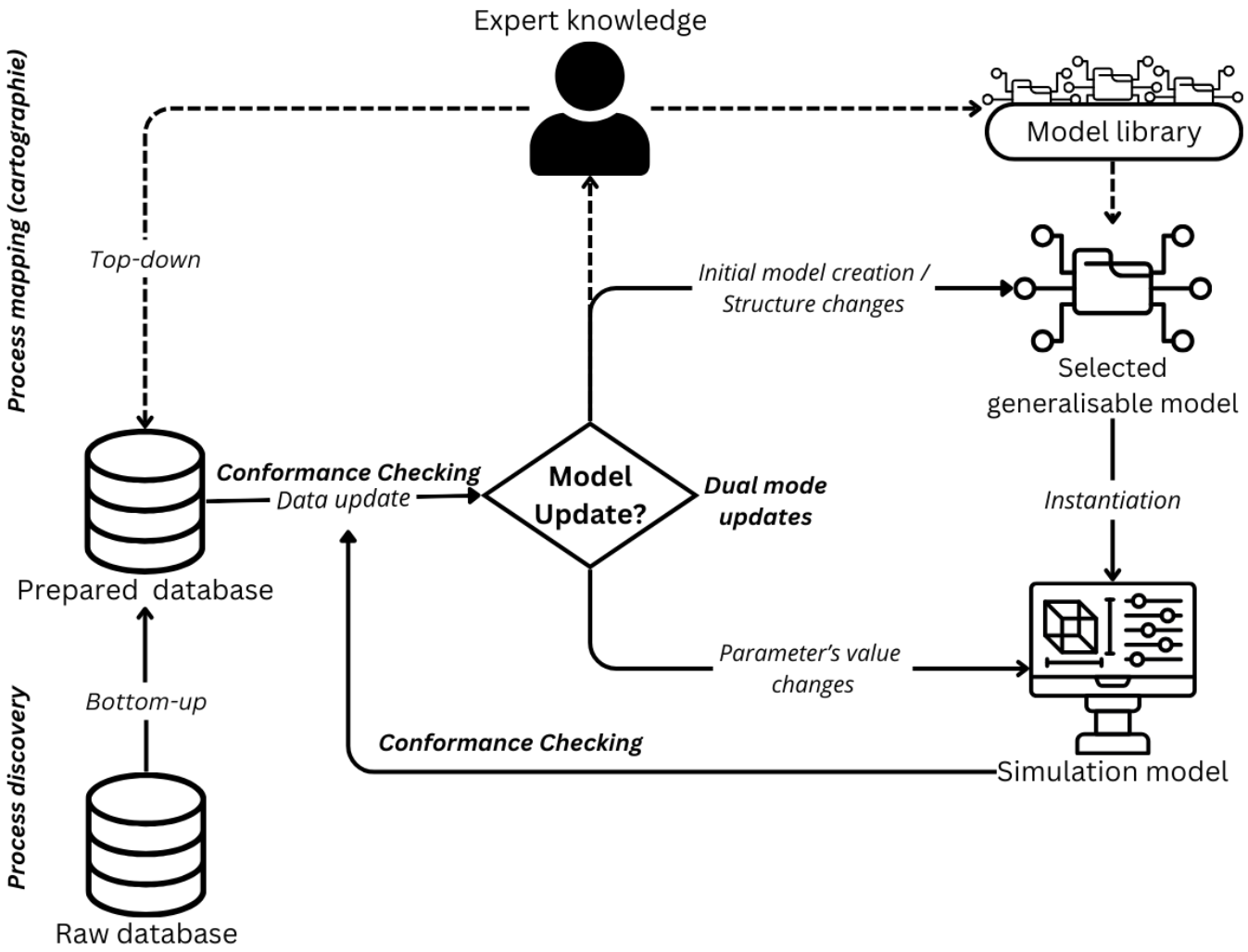
Agenda

- DT and Human
- JUNEAU project overview
- Patient arrival model
- ED organisation simulation model
- **Model evolution**
- Conclusions & Perspectives

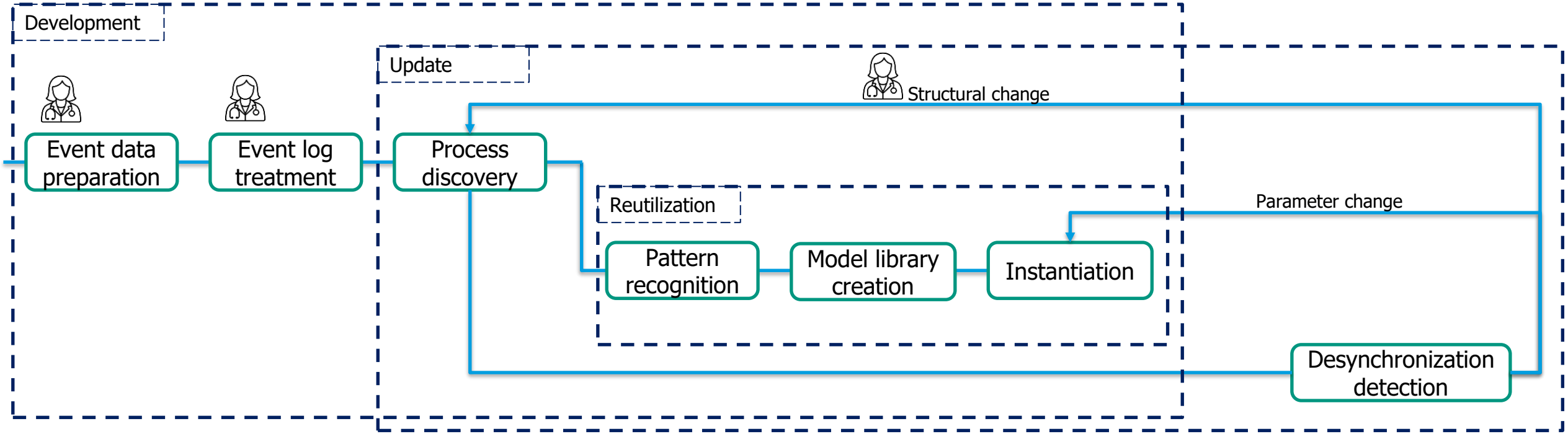
Model evolution



Model evolution



Model evolution



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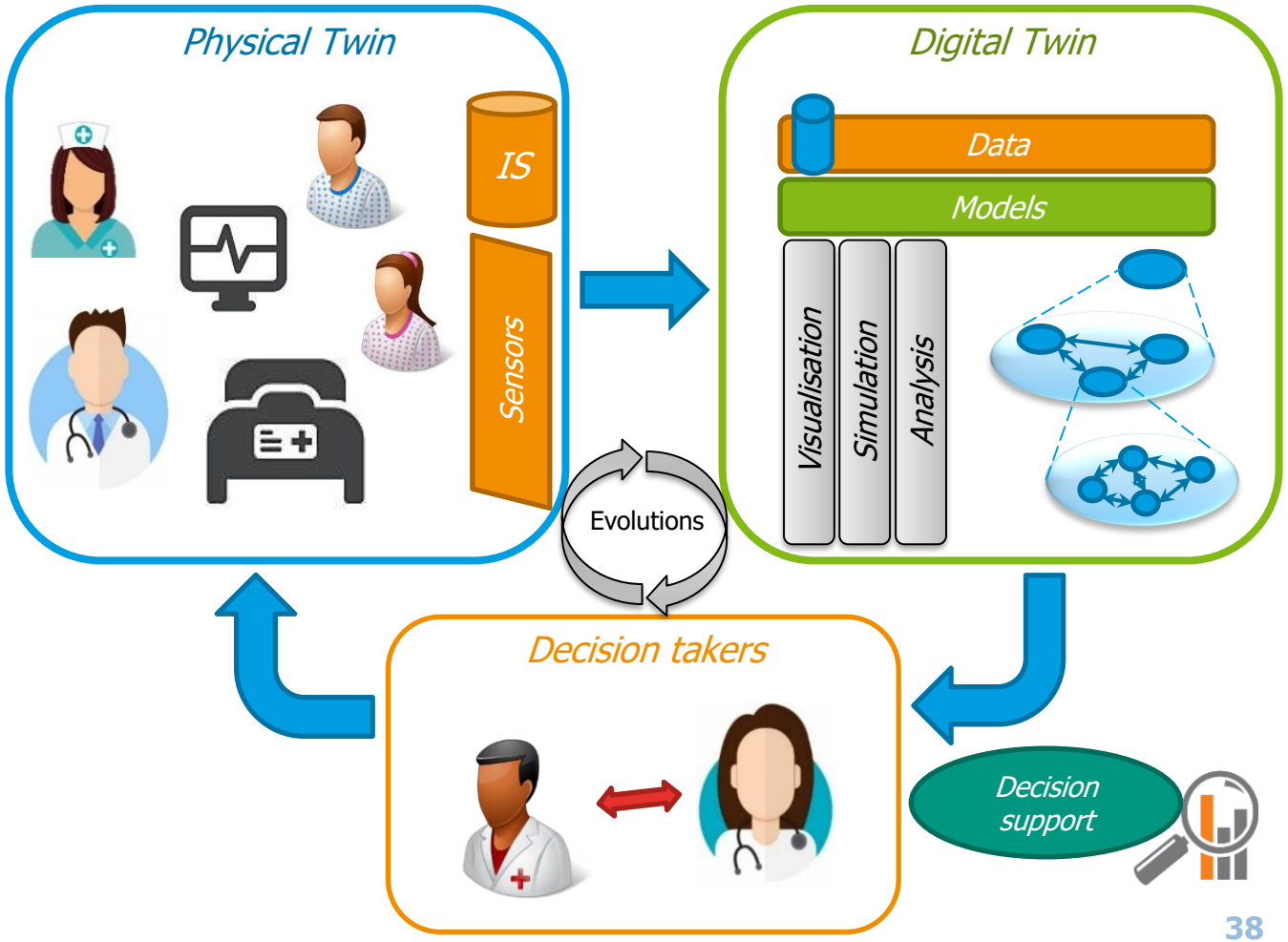
Conclusions & Perspectives

- Position of human in the DT:
  - Decision-maker, agent, supervisor of the DT, etc.
  - Human-Simulation
- Homogenous behaviour
  - At present, all agents of the same type always behave in the same way
  - Not true in reality…
- Impact of DT on works
  - Cognitive ergonomic
  - Change management
  - New paradigms ?



Perspectives

Fatigue evaluation along time and among agents

Interruptions **increase individual fatigue** accumulation (additional displacements)

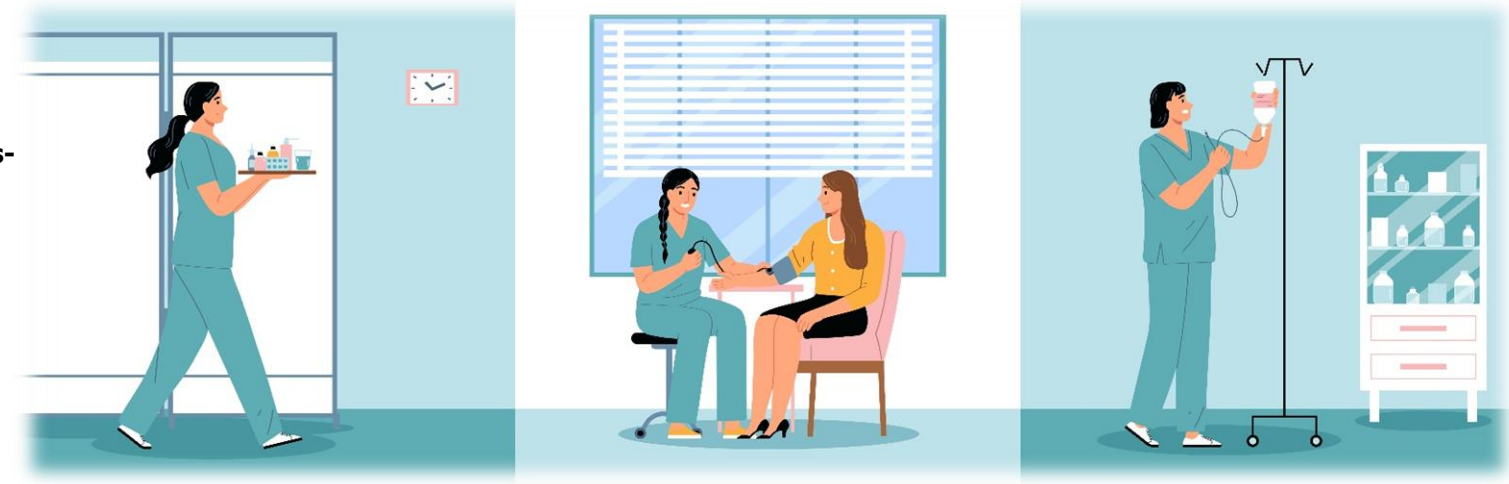
Interruptions generally **degrade performance** and are associated with an increase in the average **treatment time**

More **fatigued nurses** generate **more interruptions**, a self-reinforcing fatigue feedback loop (Lotka component)

Cognitive stress persists beyond the **interruption** event, reflecting a memory effect (Volterra component)

Variations in accumulated fatigue levels at the end of the day may also be **explained** by the timing and **location** of each **nurse's break**

A **beneficial collective effect** emerges only when the **social boost is elevate**



Y. Paredes-Astudillo & G. Bouleux **Agents-based simulation and BLV diffusion coupling approach for nurses interruptions effect behavior in an emergency department**, CoDIT'26

GDR Groupement de recherche
MACS Modélisation, Analyse et Conduite des Systèmes dynamiques

JUNEAU
JUmeau Numérique pour un sErvice d'Accueil des Urgences

Digital twin for human-based organisation
An example on Emergency Department

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