

Systemic Digital Twins for Mastering Complex Industrial Operations & Strategy

How to Optimize Industrial Operations? From Modelling to Simulation of Complex Industrial Systems

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February 2025



Systemic
Intelligence





Systemic Intelligence

Who are we?

Core competences

Systems
architecture

Enterprise
architecture &
transformation

Iterative &
collaborative
systems
engineering

Agile@scale
architecture

Product lines
architecture

Model-based
systems
engineering
(MBSE)

**Systemic
digital twins**

Offers

Transformation support
Industrial system modeling
& simulation expertise
Coaching & training

Team

≈ 40
people

Income

8 M€
2023

Offices

Paris
Toulouse
Shanghai

Creation



Spin-off - 2011

Partners



On-the-job training programs

AIRBUS GROUP • ARIANE GROUPE •
NISSAN • RENAULT • SAFRAN •
SCHNEIDER ELECTRIC • STELLANTIS

CESAM method

≈ 10,000
trained professionals
for 10 years

Community



*Our systems architect
community*

Events

- CSD&M Paris & Beijing
- Industrial Enterprise
Architecture Day
- Top executive club

LinkedIn

≈ 10,000
followers

Systemic Intelligence is a part of **CESAMES group**, a spin-off of the industrial chair “Engineering of complex systems” of Ecole Polytechnique. We are specialized in **systems architecting & engineering** and propose **modeling & simulation techniques** to better mastering industrial complexity.



Systemic Intelligence

Our chief officers



Daniel KROB, chief executive officer of Systemic Intelligence, is a former institute professor in Ecole Polytechnique, the top 1st engineering university in France, currently also Distinguished Visiting Professor in Tsinghua University, the top 1st engineering university in China. He is a leading **world expert in system modeling**, recognized as Fellow of the International Council on Systems Engineering (INCOSE).



Antoine RAUZY, chief scientific & technological officer of Systemic Intelligence, is professor in CentraleSupélec in France and in the Norwegian University of Science & Technology in Norway. He is a leading **world expert in system simulation** and developed the AltaRica model-based safety technology, currently used worldwide in the industry for supporting safety studies.

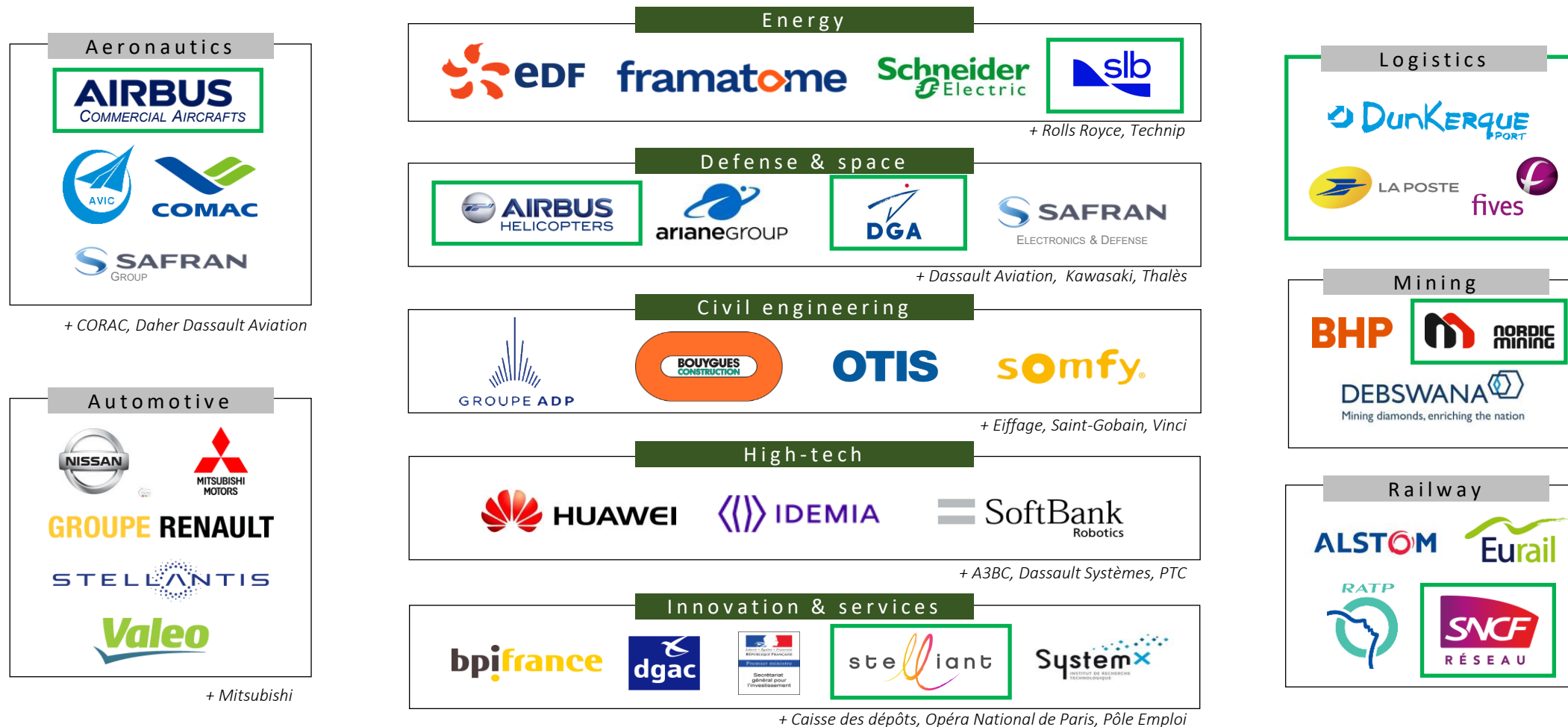




Systemic Intelligence

Our industrial ecosystem

Our first systemic
digital twin customers



Our current ecosystem of industrial customers at CESAMES group level



Systemic Intelligence

Our first customers

Our first systemic
digital twin customers



*Strategic planning for the A220
extended industrial system*



*Strategic planning of new logistics flows
within the port of Dunkirk*



*Transformation of the press
process on a national scale*



*Comparison of railway
signaling systems in situations
of traffic growth*



*Optimal design of an
automated warehouse*



*Optimization of a defense
industrial process*



*Optimal design of an
underwater mine in the
North Sea*



*Optimal design of an agile
workshop for producing
wind turbine parts*



*Analysis of the impacts of feared
events (flood, fire, cyber-attack)
on an industrial factory*

Our first examples of **industrial application** of our systemic digital twin solution

Systemic digital twins: why, what, how?



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Why

The business scope of a systemic digital twin (1/2)



- What is the optimal global architecture for an industrial system?
- What is the optimal design for a new industrial facility?
- What is the industrial evolution scenario with less risks & costs?
- What is the best way to manage an industrial process?
- What is the optimal way to manage an industrial ramp-up?
- What is the optimal industrial maintenance strategy to follow?

Examples of strategic industrial decisions



- How to optimize my industrial lead time during operations?
- How to minimize non quality during industrial operations?
- How to determine the root causes of an operational inefficiency?
- How to optimally reconfigure my industrial production?
- How to minimize energy & wastes during industrial operations?
- How to decrease environmental footprint during industrial operations?

Examples of operational & tactical industrial decisions

Optimization of industrial operations rely on many different types of **operational, tactical & strategic industrial decisions**

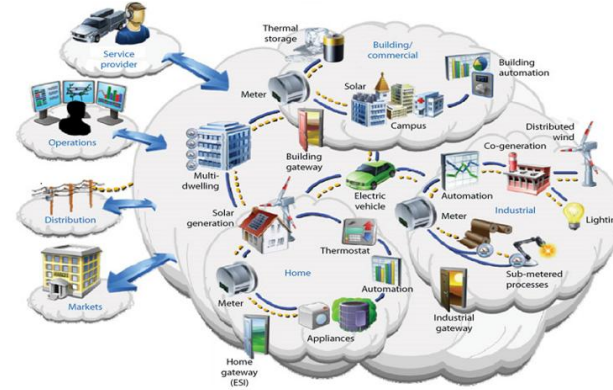


Why

The business scope of a systemic digital twin (2/2)



*Optimizing
complex supply chains*



Optimizing complex operations and maintenance



Optimizing complex manufacturing



Minimizing industrial risk



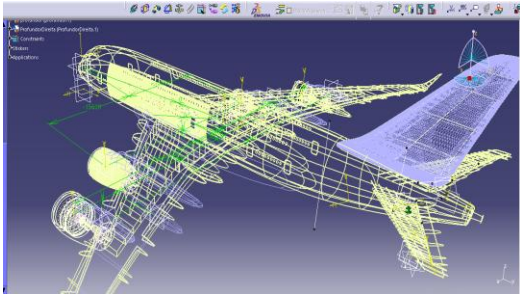

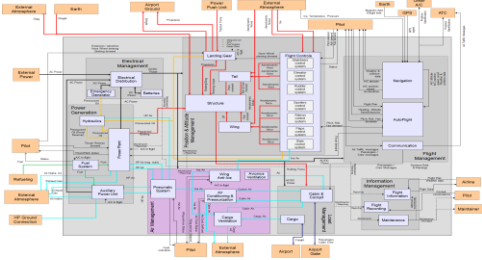
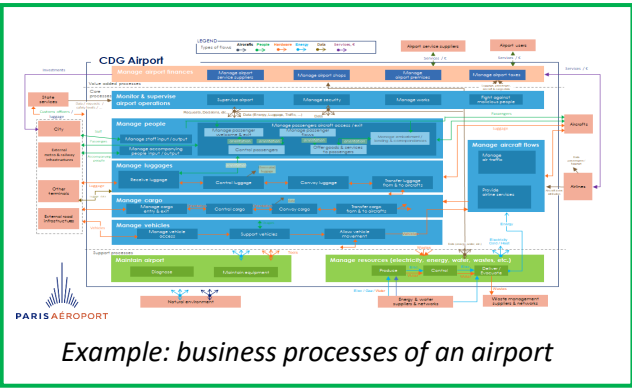
Modern industries must **optimize complex interdependent operational ecosystems**, such as their supply chain, their production systems, their distribution systems, their customer operations, their maintenance systems, etc., taking into consideration **complex economical, political, social, technological, legal & environmental constraints** from a tactical and strategic perspective.



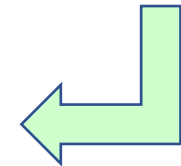


What

The functional scope of a systemic digital twin (1/2)

	Industrial products	Industrial processes
Geometry (where is located the system)	 <p><i>Example: geometric model of an aircraft</i></p>	 <p><i>Example: geometric model of an airport</i></p>
Behaviour (what is doing the system)	 <p><i>Example: functional model of an aircraft</i></p>	 <p><i>Example: business processes of an airport</i></p>

Systemic
digital twins



Systemic digital twins address these challenges by **simulating & optimizing industrial processes** of **complex industrial systems**



What

The functional scope of a systemic digital twin (2/2)

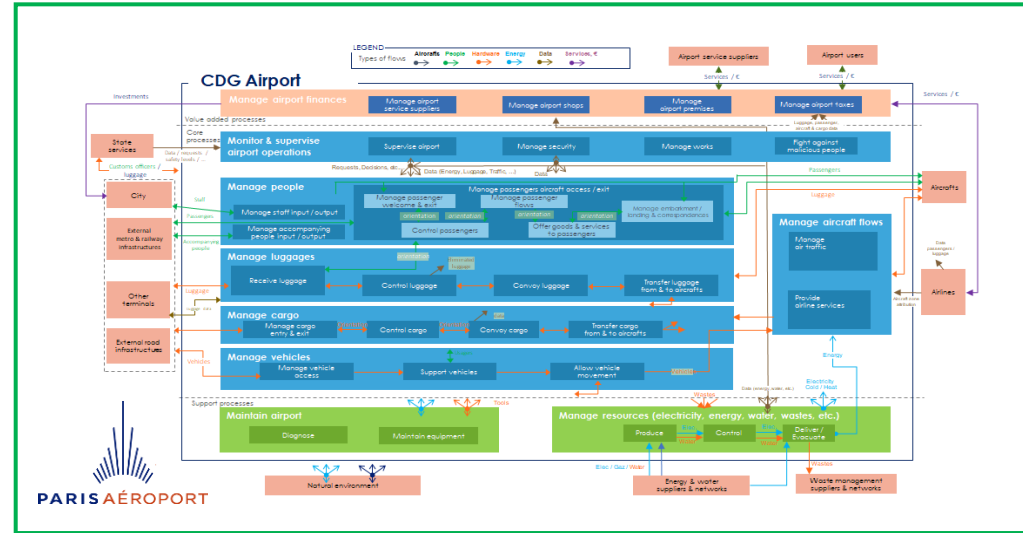
Systemic digital twins



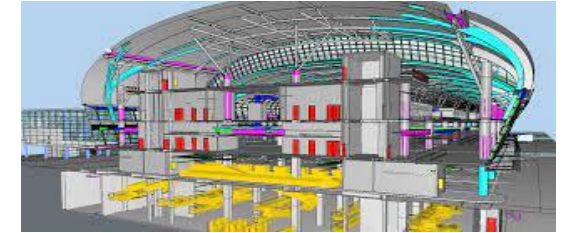
IOT & RFID infrastructure



Smart devices



Business processes



Digital mock-ups



Building Information Modeling (BIM)

Our functional digital twin philosophy where business processes are at the core of a digital twin

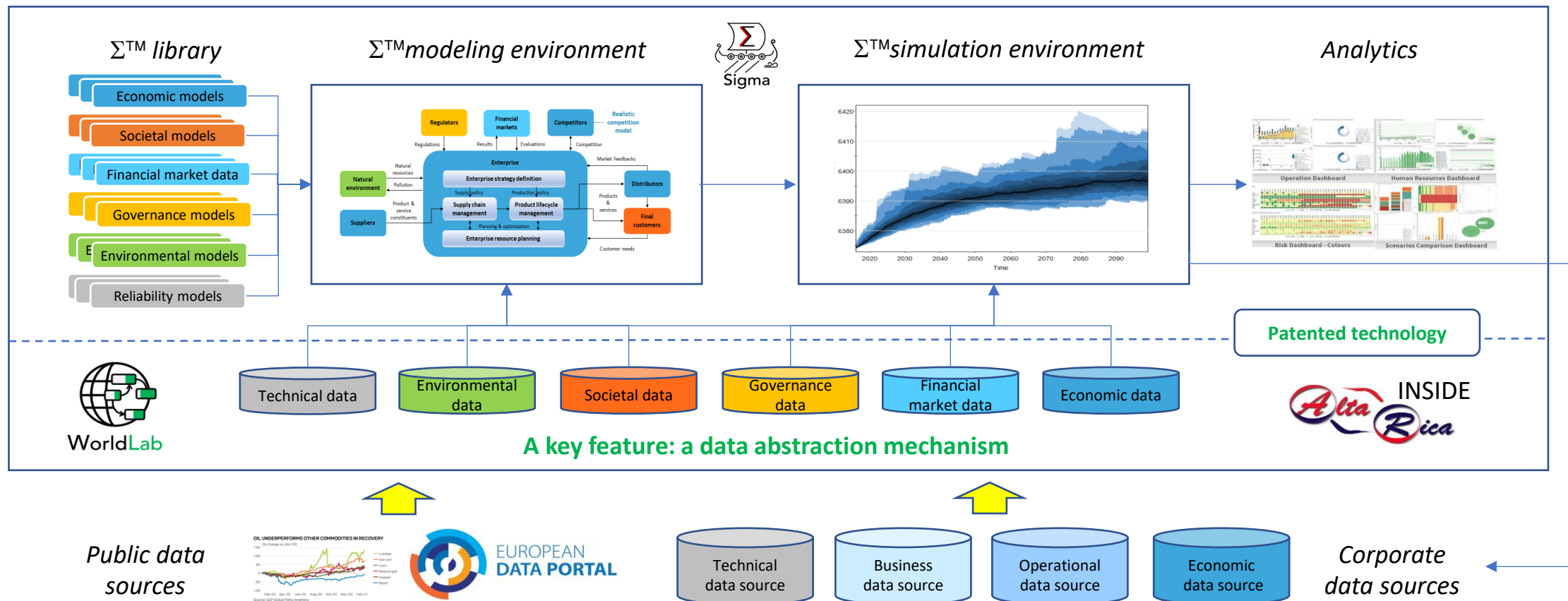
Contrarily to the market (e.g. Ansys, Bosch, Dassault Systèmes, PTC, Siemens, etc.) that focuses either on data-related infrastructure or on geometric representations, we believe that digital twins must use a **functional point of view**: they shall be able to **model & simulate the behavior, i.e. the business processes, of an industrial system**, starting from operational data and ending by enriching decision dashboards or digital mock-ups, which put business models at the core of a digital twin. This is why we took an **enterprise architecture behavioral approach** which is our key difference with respect to existing digital twin technology.





How

The technological scope of a systemic digital twin (1/2)

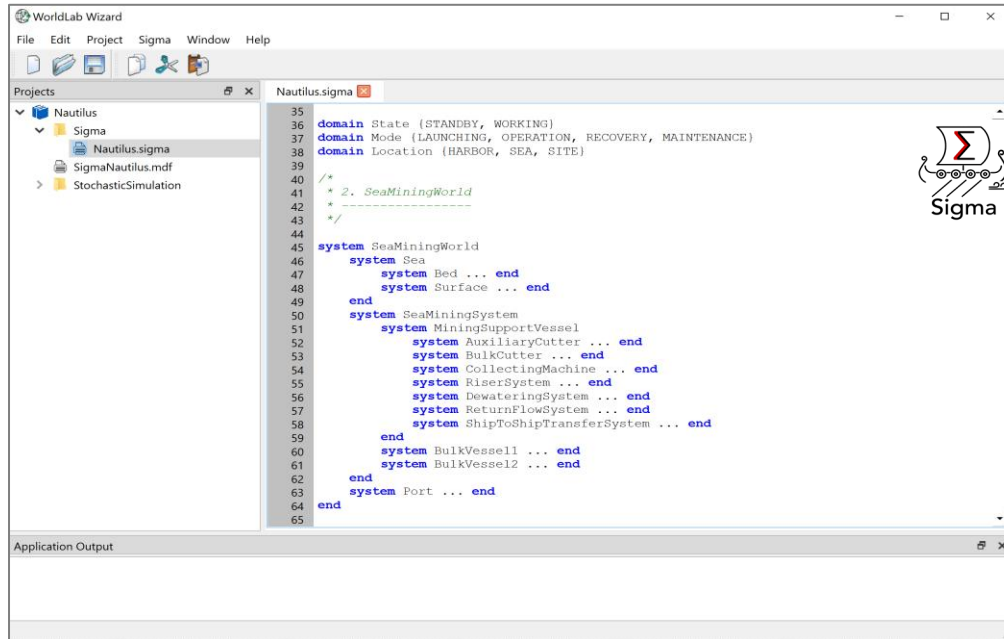


To support our vision, we developed the **WorldLab™ patented technology** – built on the **proven infrastructure of the AltaRica safety & reliability analysis tool**, developed by Antoine RAUZY during the last 20 years and industrially used in many industrial sectors – which is a **systemic intelligence workshop** that offers systemic modelling and scenario stochastic simulation & evaluation capabilities.

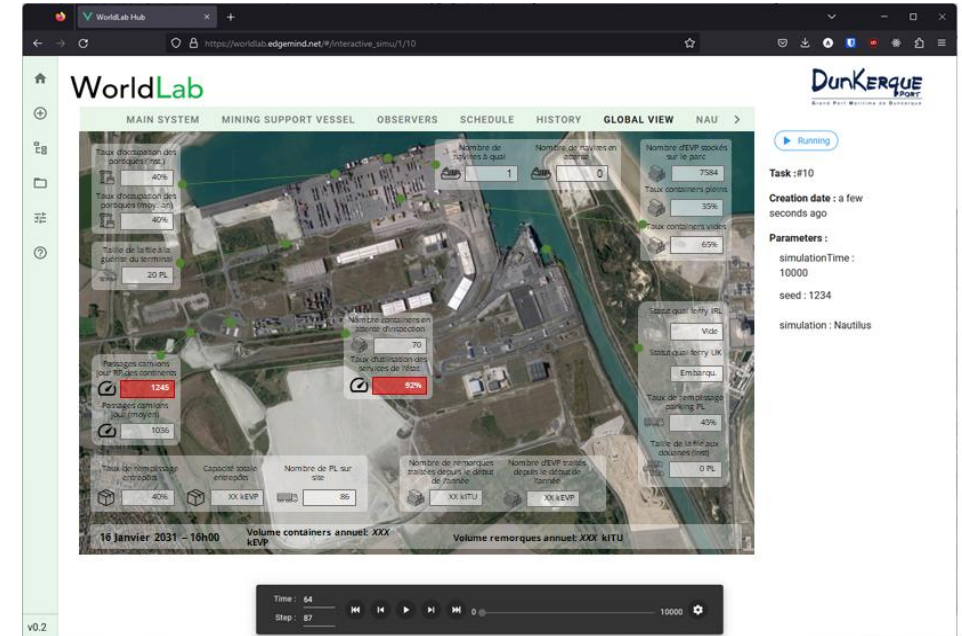


How

The technological scope of a systemic digital twin (2/2)



WorldLab™ Workshop



WorldLab™ Hub

The **WorldLab™ technology** has two sides dedicated to two different types of users: 1) the **WorldLab™ Workshop** is a system modeling & simulation standalone workshop where a **system modeling engineer** can model a given industrial system, using our system specification language Σ^{TM} , and prototype the associated systemic digital twin, 2) the **WorldLab™ Hub**, generated through the WorldLab™ Workshop, is the Web interface dedicated to the **business users** where one can simulate a systemic digital twin, evaluate business indicators and compare business scenarios associated with the modeled industrial system.



How

The Σ^{TM} modeling language at the core of WorldLabTM (1/2)



```
1 system World
2   system Supplier
3     int rawMaterial(init = 0);
4   end
5   system Producer
6     int order(init = 0);
7     int rawMaterial(init = 0);
8     int product(init = 0);
9   end
10  system Consumer
11    int order(init = 0);
12    int product(init = 0);
13  end
14 end
```

*Specification of a hierarchy
of systems in Σ^{TM}*

```
1 system World.Supplier
2   int rawMaterial(init = 0);
3   bool renewing(init = false);
4 end
5
6 activity World.Supplier.RenewRawMaterialStock
7   trigger:
8     return rawMaterial<=1000 and not renewing; ← Condition that
9   start:                                     triggers the activity
10    renewing = true; ← What shall be done when the activity starts
11  completion: {
12    renewing = false;
13    rawMaterial += 100; ← What shall be done when the activity stops
14  }
15  duration:
16    return 30; ← Duration of the activity (in units of time)
17 end
```

Specification of a business process – as an activity – in Σ^{TM}

The Σ^{TM} **formal modeling language** allows naturally to **specify** the **hierarchical structure** and the **behaviors**, that is to say the business processes, of a given industrial system, but also the **end-user interface** with the **business indicators & alerts** that shall be computed and shown to the business users during the use of a systemic digital twin.





How

The Σ^{TM} modeling language at the core of WorldLabTM (2/2)



```
1 activity World.Consumer.ConsumeProduct
2   trigger:
3     return product >= 1000 and not consuming;
4   start:
5     consuming = true;
6   completion: {
7     consuming = false;
8     product -= uniformDeviate(1, 2.5);
9   }
10  duration:
11    return 1;
12 end
```

Example of a stochastic quantity with explicit probabilistic distribution

```
1 activity World.Consumer.ConsumeProduct
2   trigger:
3     return product >= 1000 and not consuming;
4   start:
5     consuming = true;
6   completion: {
7     consuming = false;
8     product -= 1;
9   }
10  duration:
11    return triangularDeviate(1, 5, 2);
12 end
```

Example of a stochastic duration with explicit probabilistic distribution

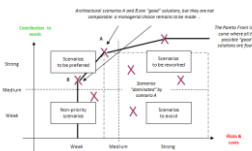
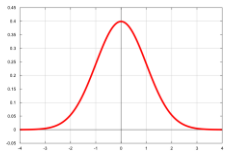
Stochastic behaviors can be captured within Σ^{TM} in two different ways, either via variables manipulated by **activities** or via **durations**. One can express in Σ^{TM} such stochastic behaviors either through a number of **exact probabilistic distributions** (e.g. Normal laws, uniform laws, exponential laws, etc.) or through **empirical distributions** (i.e. experimental timed sequences).





How

The key unique features of WorldLab™



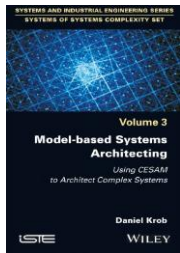
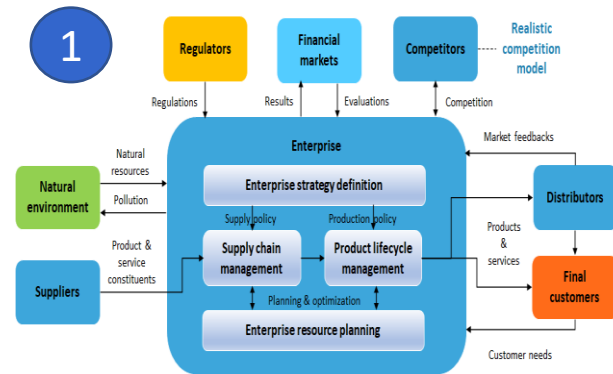
- **Simplicity & Maintainability** – A systemic digital twin is specified in the **object-oriented modeling language Σ^{TM}** which is quite simple to use to any person with an algorithmic-design background. This choice also allows to **easily develop & maintain the evolution** of a systemic digital twin among time which becomes similar to software engineering.
- **Heterogeneity** – A systemic digital twin can integrate **various heterogeneous features**, such as technical functions, maintenance policies, societal behaviors, financial market evolutions, regulatory strategies or meteorologic conditions, into a **single unique systemic model**, allowing to analyze a given industrial system from all these various perspectives.
- **Concurrency & Time** – This modeling language especially allows to manage **concurrent industrial activities** and express **explicit durations** for timed transformation activities of an industrial system, which is currently not offered by the existing similar languages.
- **Hazards** – **Hazards** can be effectively captured in a systemic digital twin: each variable specified in the Σ^{TM} modeling language can be a random variable with a specific probability distribution – either explicit or pragmatic – allowing to capture **random quantities & random delays** and to manage **stochastic simulations** for a given industrial system.
- **Scenarios Evaluation & Prioritization** – The WorldLab™ platform proposes dedicated features for **evaluating & prioritizing business evolution scenarios** which allow to achieve **multi-criteria optimization**, e.g. maximizing production when minimizing delays & energy consumption, with respect to a given industrial system.





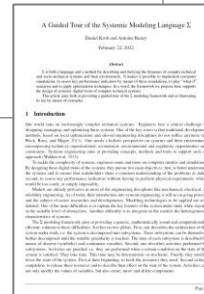
In practice

Systemic digital twins do connect MBSE to simulation

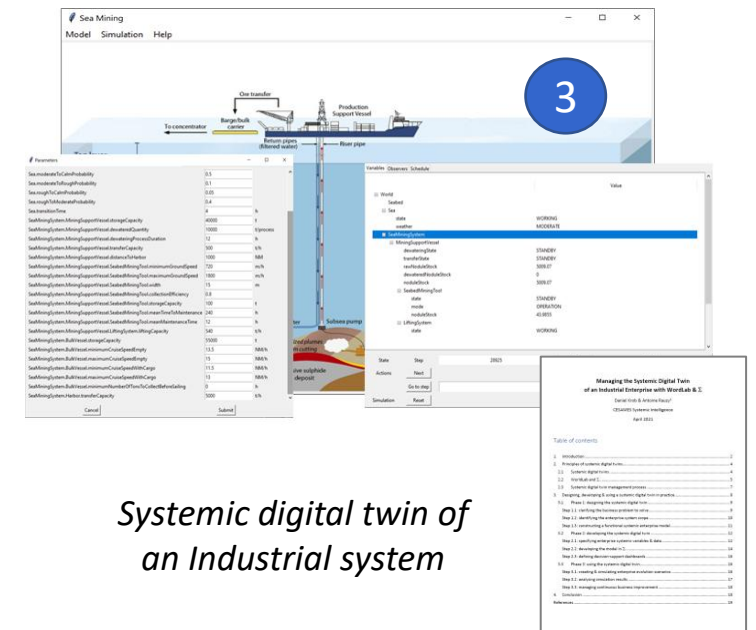


MBSE model of an industrial system

```
1 system World
2   system Supplier ... end
3   system Producer ... end
4   system Consumer ... end
5 end
6
7 system World.Supplier
8   int rawMaterial (init = 0);
9 end
10
11 system World.Producer
12   int order (init = 0);
13   int rawMaterial (init = 0);
14   int product (init = 0);
15 end
16
17 system World.Consumer
18   int product (init = 0);
19 end
```



Σ^{TM} model of an industrial system



Systemic digital twin of an Industrial system

Principle of the development of a systemic digital twin of an industrial system with Σ^{TM} and WorldLabTM

The **WorldLabTM technology** especially allows to **produce automatically systemic digital twins** of an industrial system from a **MBSE model** through a **specification** designed in our **Σ^{TM} formal modeling language**.

A case study: design of an automated warehouse



Systemic
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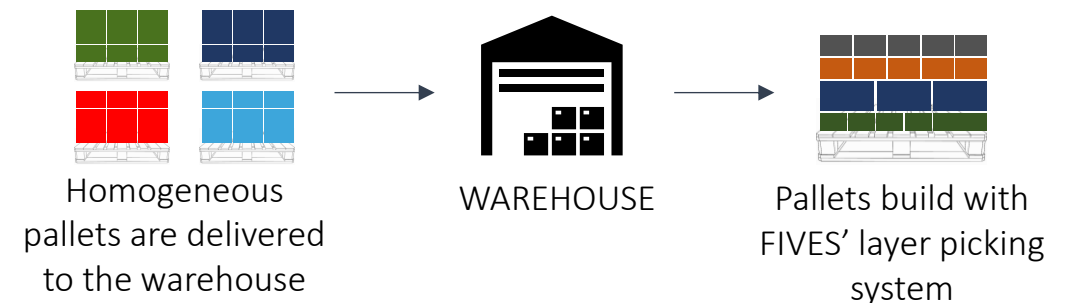
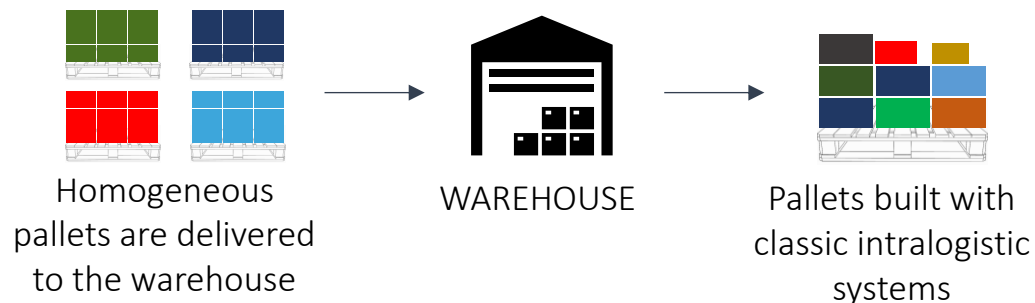


A case study: the design of an automated warehouse

A bit of context



- **New generation automated warehouses** allow logistic operators to supply points of sales in dense urban zones.
- They need to be **compact and fast** to cope with high demand & small physical footprint.
- Usually, these warehouses produces pallets which are **built from individual boxes**.
- These boxes are either **built through piece or case picking** thanks to an ASRS / an AMR fleet and picking stations.
- **Fives Syleps** wants to introduce a new mode of operation with a system able to **process entire layers of a pallet** at once.





A case study: the design of an automated warehouse

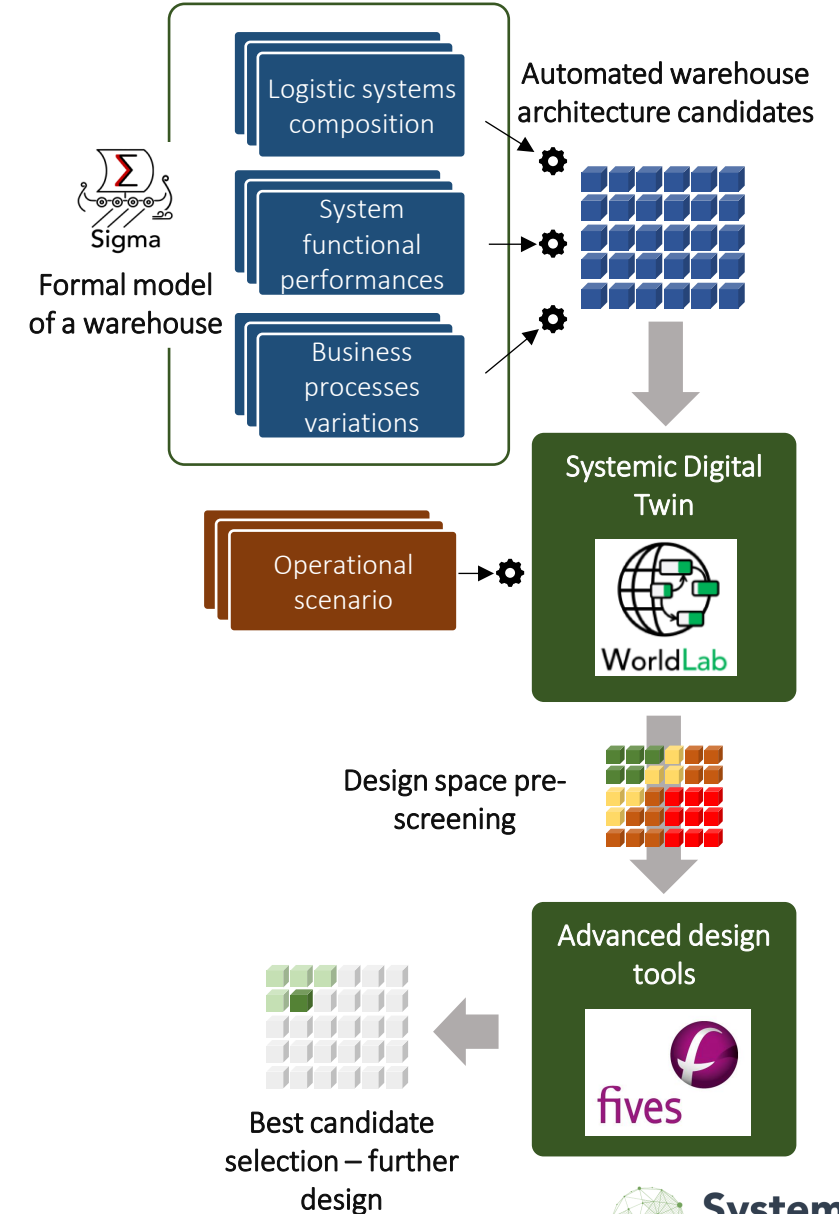
Why a systemic digital twin ?

Automated warehouse with layer picking technology = **complex system**:

- Difficulties to grasp the consequences of **local decisions** on the **rest of the system**
- Difficulties to understand the effect of **fluctuating operating conditions**, on the **overall performances** of the system

FIVES needed a tool they can **use in preliminary design**, able to conduct thorough **design space exploration** at a **macroscopic level**:

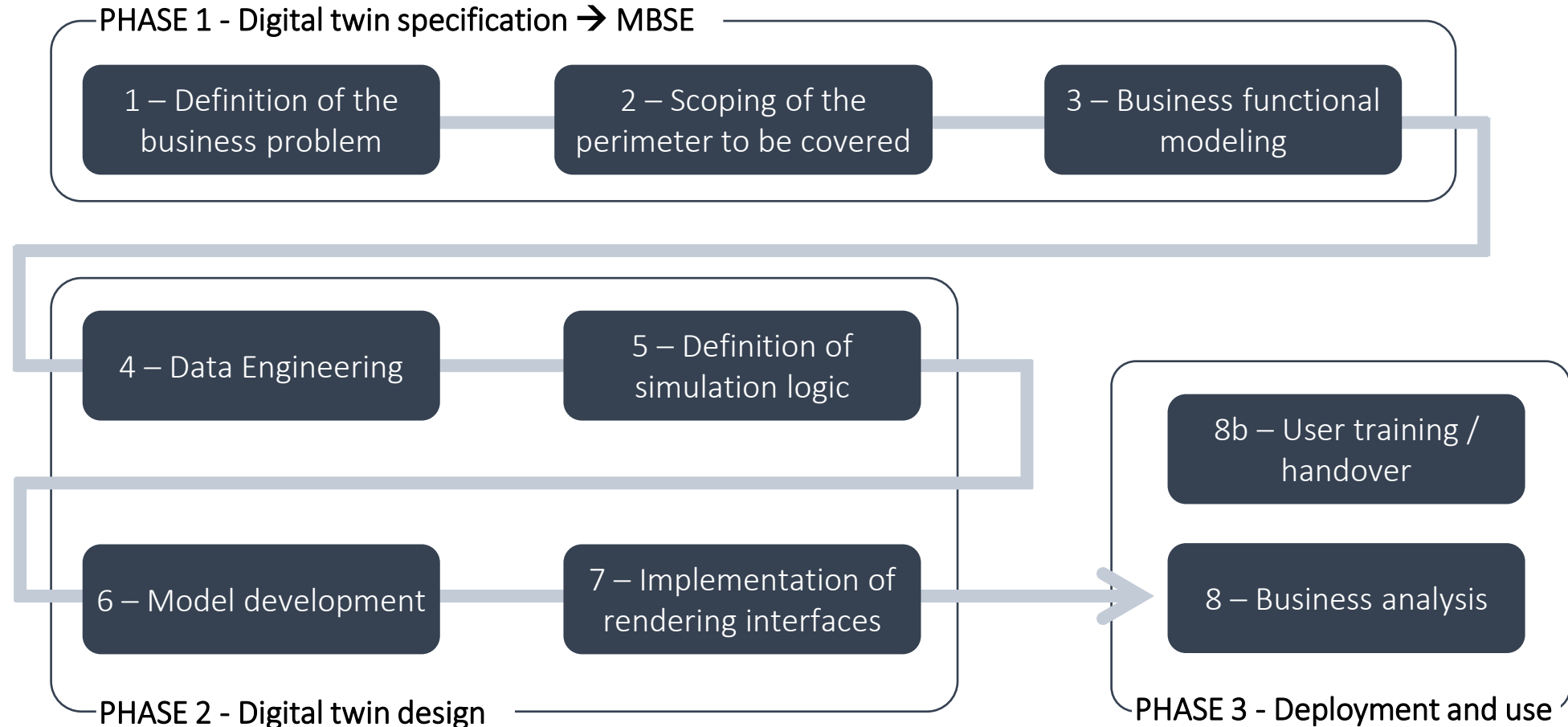
- **To :**
 - take the best **high-level architectural** design decisions
 - **avoid wasting time** performing detailed and costly analyses on warehouses configurations that were not viable.
- **For :**
 - the **research and development** of new “turn-key” solutions integrating this kind of system,
 - facilitated answers in **tender processes**





A case study: the design of an automated warehouse

Systemic Digital Twin simplified development & release cycle



The approach followed for the development of a systemic digital twin is **articulated around 3 main phases**. This process structure is **common to all our implementation projects**.



Phase 1: Digital twin specification

Definition of the business problem

Consistently with any **MBSE approach**, a key step of the **digital twin specification** consists in **formalizing the business strategy** through the **use cases** of the system of interest that shall be modeled, simulated & analyzed with a systemic digital twin



Use case 1 – Analysis of the impact of load and delivery profiles variation :

- For a given architecture, what would be the impact of a higher-than-usual load – of various amplitude - on warehouse activities ?
- Deliveries can be sometimes very regular, or delivery trucks can arrive by batch. What is the impact of delivery fragmentation on warehouse activities ?

Use case 2 – Optimization of logistic assets fleets and process variation

For a predictive and fixed intensity of warehouse activities, to maximize the utilization rate of costly assets and minimize buffer inflation

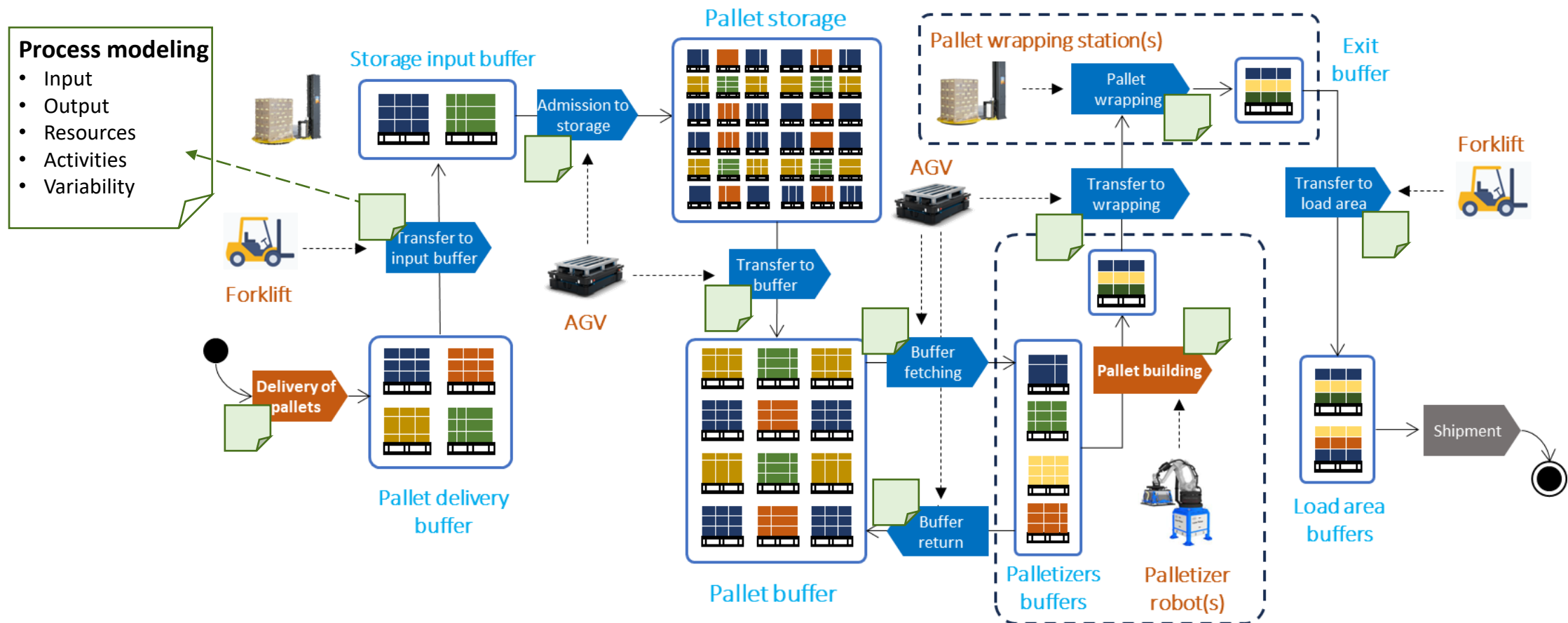
- What is the optimum size for the various fleets of assets ?
- What is the best automation-to-human ratio for the logistic activities in the warehouse ?



Phase 1: Digital twin specification

Scoping of the perimeter to be covered & business process modeling

SYSTEM OF INTEREST : Automated warehouse equipped with a layer picking system



The **flow of goods** within the warehouse has been traced, from an **entry point** to an **exit point**. Every step involved in their processing has been **characterized from a business perspective**, so that its **behavior** can later be **implemented in Σ^{TM}** .





Once the model is compiled with WorldLab™, users run simulations over **one day of operation** :

- [illegible]



Phase 2: Digital twin design

Σ^{TM} model development - takeaways

The key use cases of the digital twin involve the **assessment of indicators**, taking into account **phenomena that feature uncertainties**.

This is possible with the **stochastic simulation** capabilities of **WorldLab**

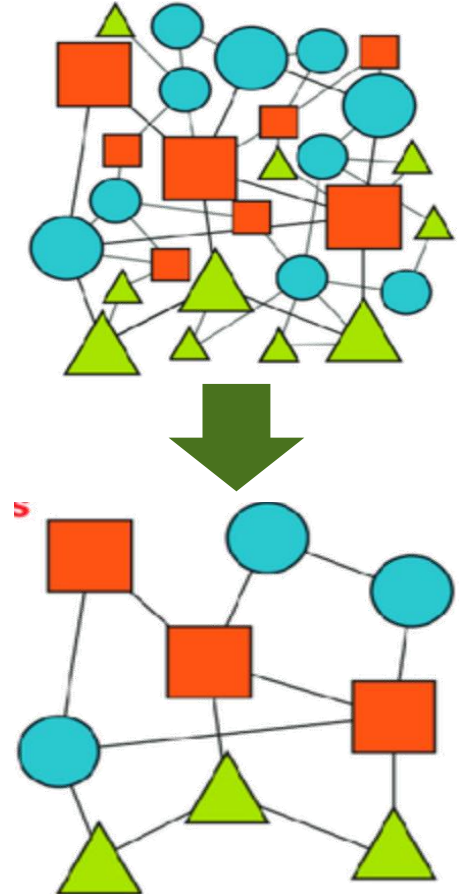
However, a day's worth of operations must be simulable in a **very short amount of time** :

- The main pitfall would be to pick a **too-detailed level of abstraction**
- However, being **too “high level”** would cause us to **miss important issues**

To the structural abstraction is added a **time abstraction** : The model allows to simulate activities “atomically”, by **15min increments**.

A **capacity approach** was selected: for each time step, each fleet of asset has a **limited number of operations** they can perform:

- The palletizers can process X layers,
- The forklifts and the AMRs have a limited numbers of “capability points” which they spend on scheduled logistic operations
- The wrappers can wrap Y pallets
- Etc.



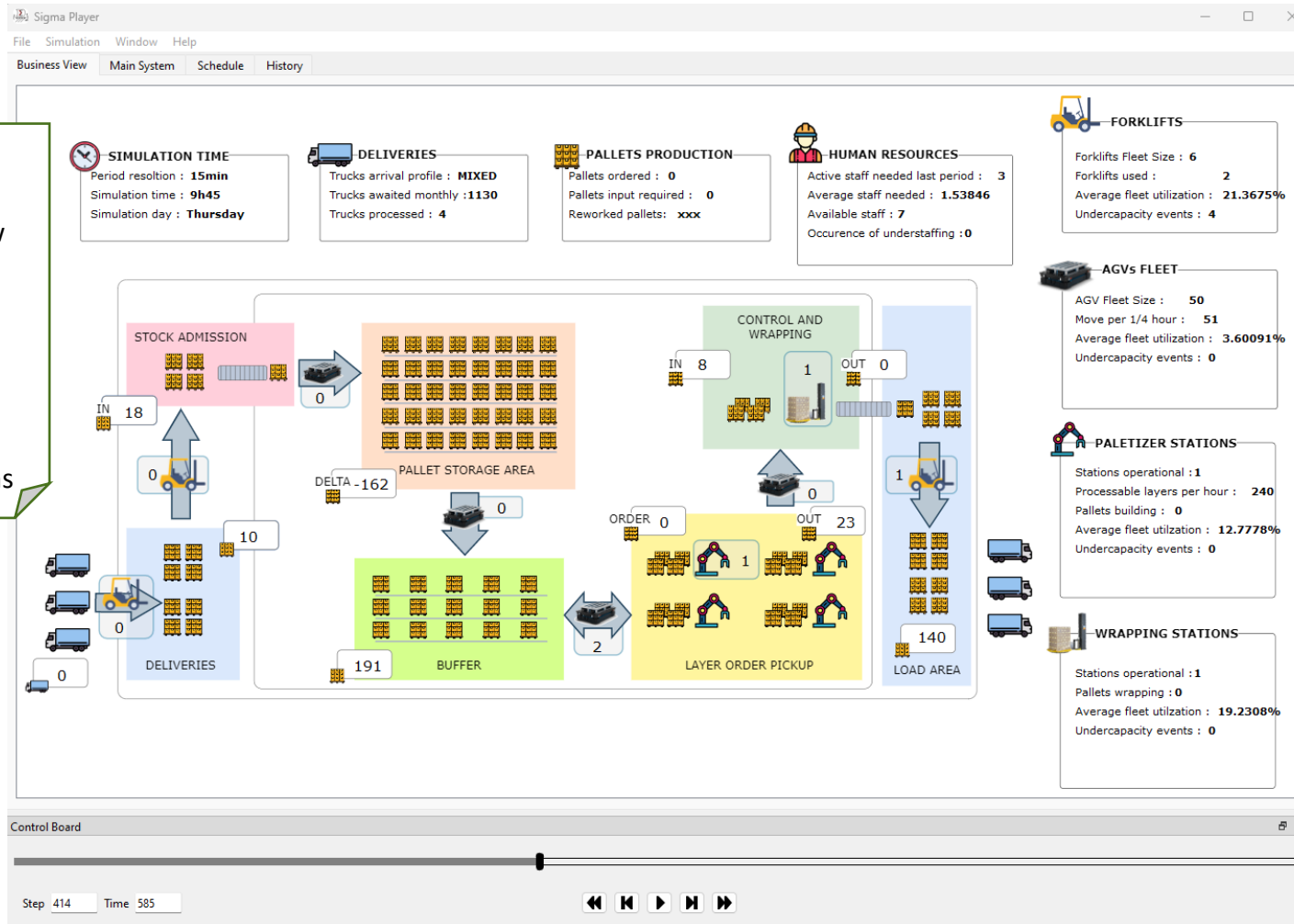


Phase 2: Digital twin design

User interface for interactive simulations

Model key parameters

- Weekly pallets flow
- Delivery profiles
- Quantity of staff
- Fleets sizes:
 - Forklifts
 - AGVs
 - Palletizers
 - Wrapper stations



- **Step-by-step** execution of the simulation
- Projecting **variables & metrics** on custom interfaces
- Access to model variables & metrics using an **explorer**
- Helps **understand and explain** how the model works
- Allows to **study the context** (or cause) of an **inefficiency / bottleneck**
- Only **one parameter set** at a time – not well suited for parametric exploration or optimization.



Phase 3: Deployment and use

Use case 1: Context & questions to answer

Context : we have a **medium-sized warehouse** – which key features are displayed here.

This warehouse **behaves well** for « nominal » loads, under ideal supplies delivery profiles.

- The load rate of human resources is around 40%, and AGVs is 60%. **Peak capacity is rarely reached.**
- There is **no accumulation in key buffers**: the delivery area, and the palletizers orders backlog.

Q1 : How well will this warehouse respond in case of a high intensity event (ie. black friday) ?

Q2 : How well will this warehouse respond in case of some difficulties of the suppliers to deliver supplies on a regular basis ?

Deliveries: uniform



Pallets : 2 700 / week avg



Palletizers: 8 units



HR: 7 workers



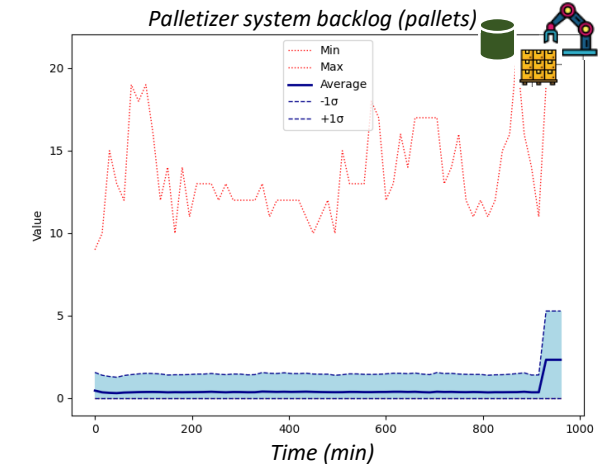
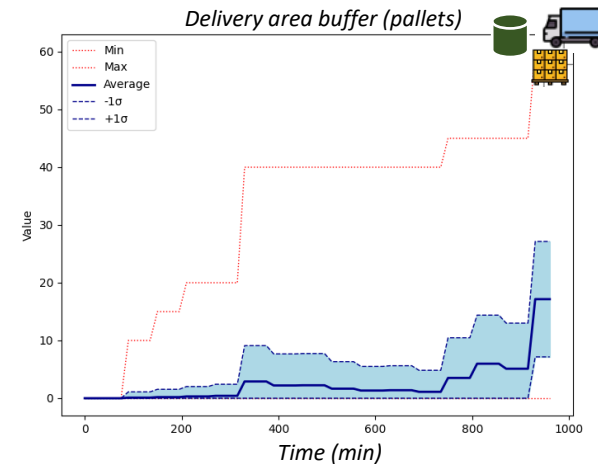
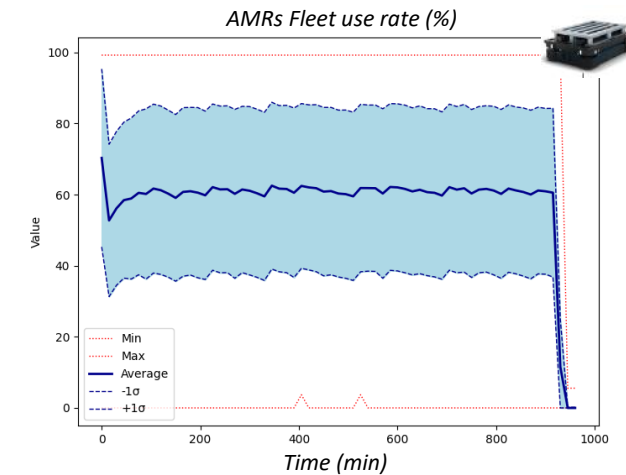
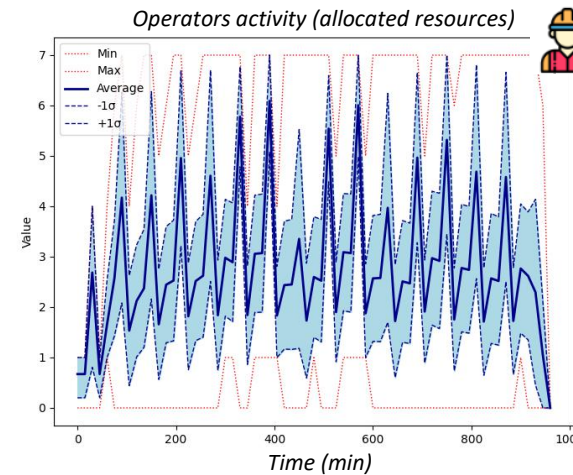
Forklifts: 6 units



AMR: 18 units



Wrappers: 2 units





Phase 3: Deployment and use

Use case 1 – Q1 : findings & conclusion (1/2)

Deliveries: uniform



Pallets : **4 600 / week avg**



Palletizers: 8 units



HR: 7 workers



Forklifts: 6 units



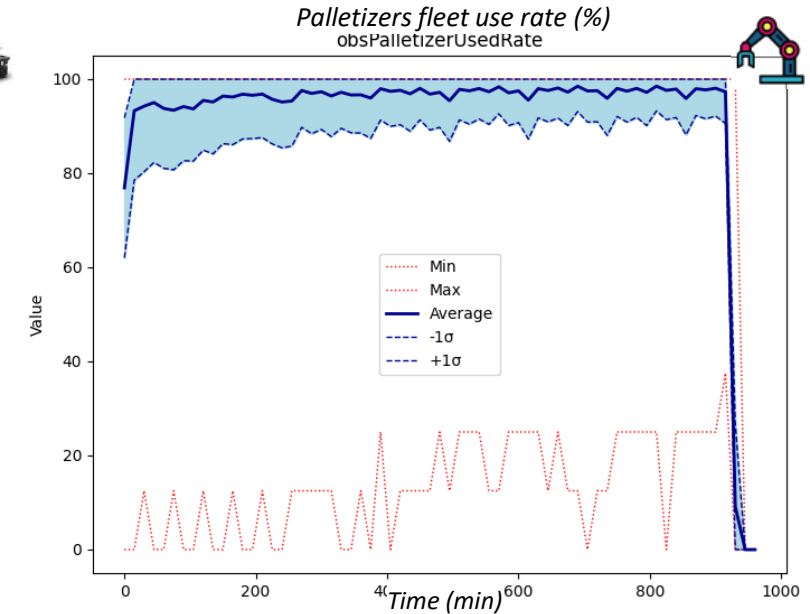
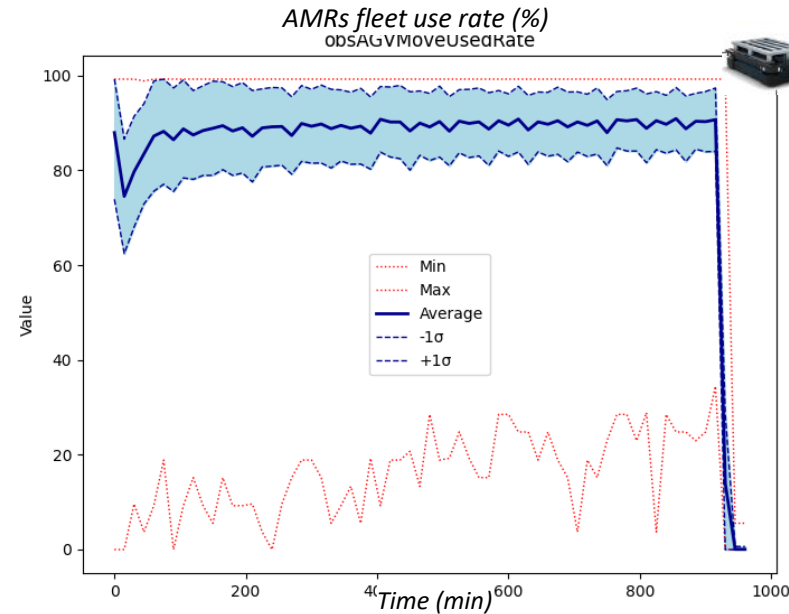
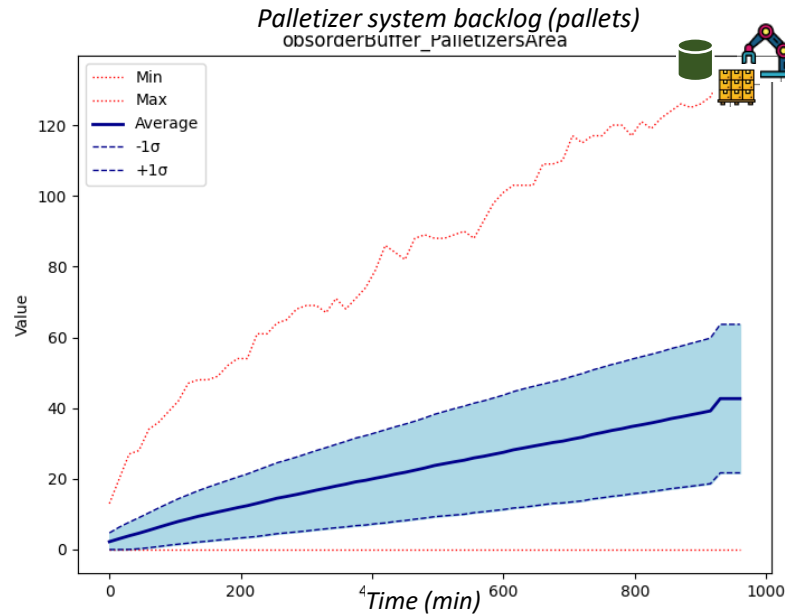
AMR: 18 units



Wrappers: 2 units



In the event of a sharp rise of warehouse activity
(+50% averaged over a week) -



- Significant **build-up of orders** in the backlog at the end of the day.
- The **palletizers** are the **cause of the bottleneck**: they run at **full capacity** throughout the day in most of the scenarios.
- The AGVs are quite solicited too (mean + std dev ~95%)





Phase 3: Deployment and use

Use case 1 – Q1 : Findings & conclusion (2/2)

In the event of a sharp rise of warehouse activity
(+50% averaged over a week) -

- The situation is **not dramatic** through !
- To accommodate these rare and predicable events, hiring more **temporary human resources** could be the way to go
- Estimation shows that the workforce would need to manually build **~120 pallets a day**
- This is a **worst case** – most scenarios do not reach **90 pallets**
- This:
 - Is much better than buying **robots that will be idle** most of the time, the rest of the year
 - Assumes that the system has been designed so that **AGVs can collaborate with workers**, and not just automated station !

Deliveries: uniform



HR: 7 workers



Pallets : **4 600 / week avg**



Forklifts: 6 units



AMR: 18 units



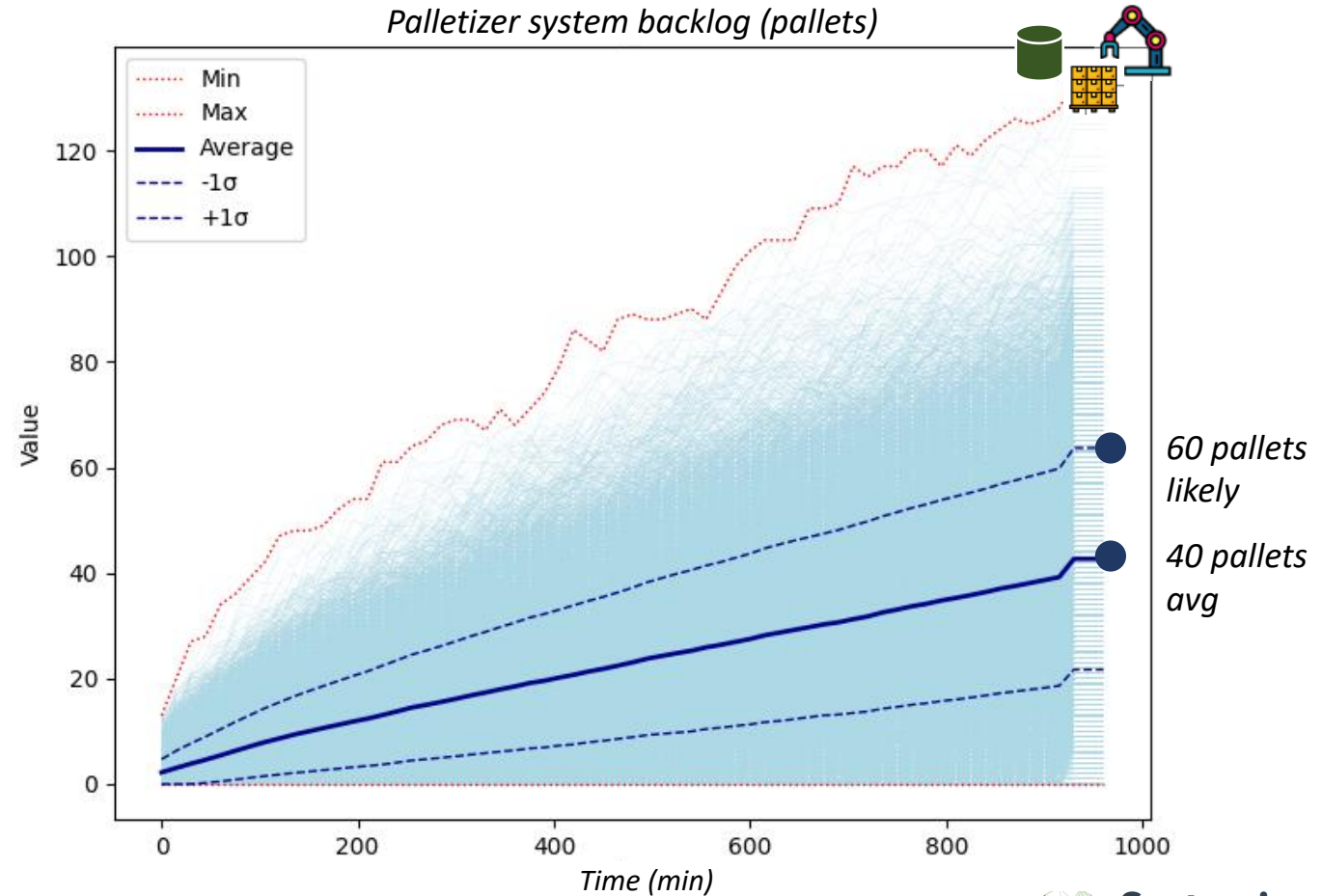
Palletizers: 8 units



Wrappers: 2 units



Palletizer system backlog (pallets)





Phase 3: Deployment and use

Use case 1 – Q2 : Findings & conclusion

Suppliers / transporters are unable to provide a uniform rate of arrival for deliveries – that tends to be clustered in short time intervals

Deliveries: clustered



HR: 7 workers



Pallets : 2 700 / week avg



Forklifts: 6 units



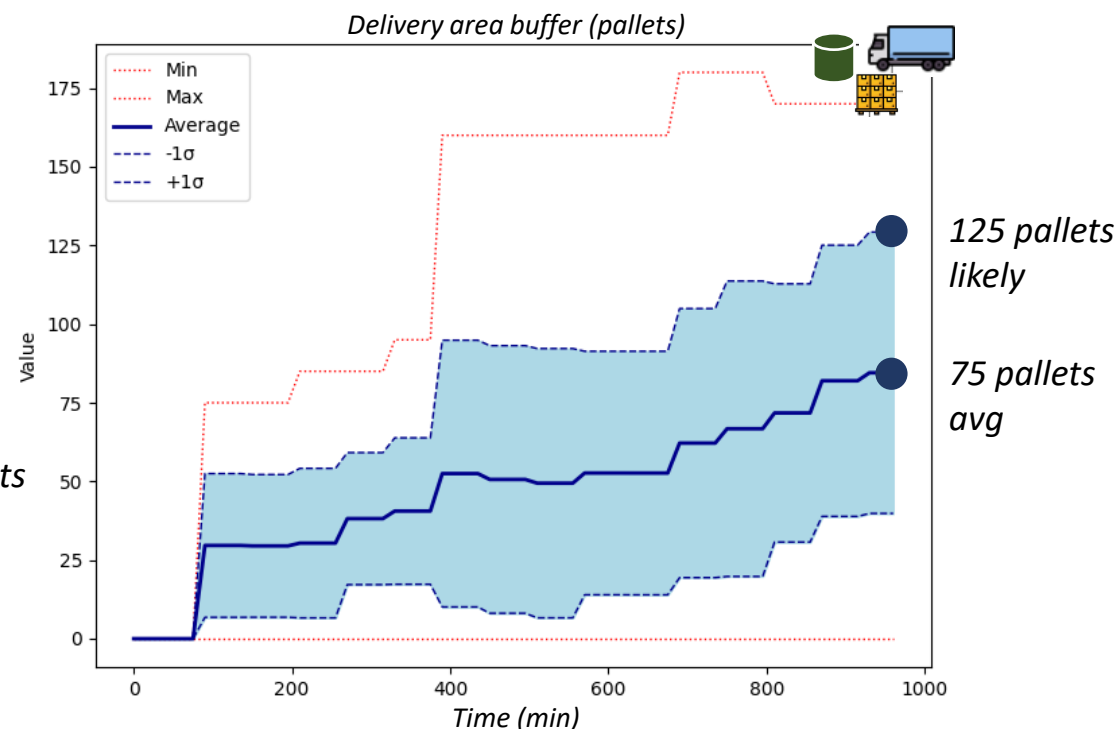
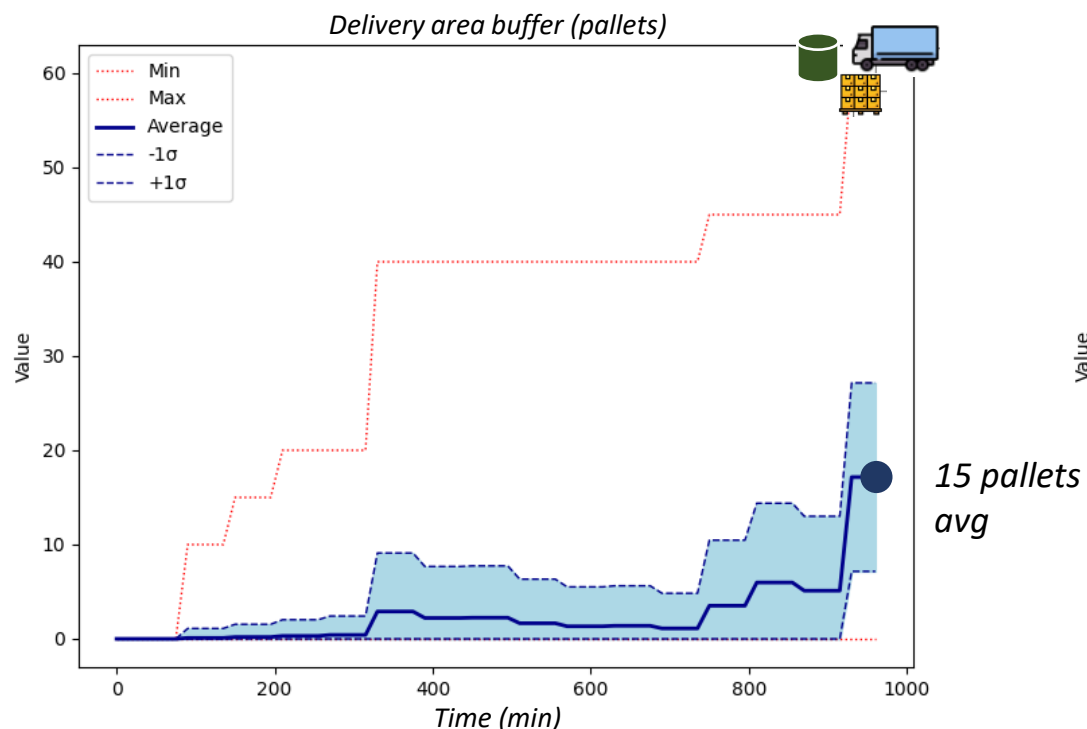
AMR: 18 units



Palletizers: 8 units



Wrappers: 2 units



- At iso production volume, the clustering of deliveries causes a substantial **accumulation of pallets in the delivery area**: There is a buildup that **cannot be compensated** throughout the day.
- However, this issue **does not affect** the ability of the warehouse **to produce and ship pallets** in the **short term**



Phase 3: Deployment and use

Use case 1 – Q2 : Findings & conclusion

Suppliers / transporters are unable to provide a uniform rate of arrival for deliveries – that tends to be clustered in short time intervals

- The issue seems to be linked to the **quantity of forklifts** available.
- However, when adding more forklifts, it is the **personnel** that becomes the cause of the **bottleneck**.
- If this situation is **exceptional**, it could be **fine to leave it** like this.
- If this situation is **recurring** – investments will have to be made to ensure the peaks of trucks' arrivals can be properly absorbed:
 - More forklifts / alternative automated system
 - More personnel to unload trucks

Deliveries: clustered

Pallets : 2 700 / week avg

Palletizers: 8 units



HR: 7 workers

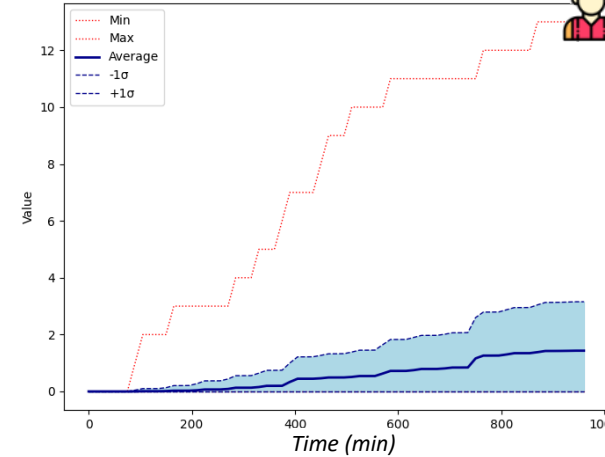
Forklifts: 6 units

AMR: 18 units

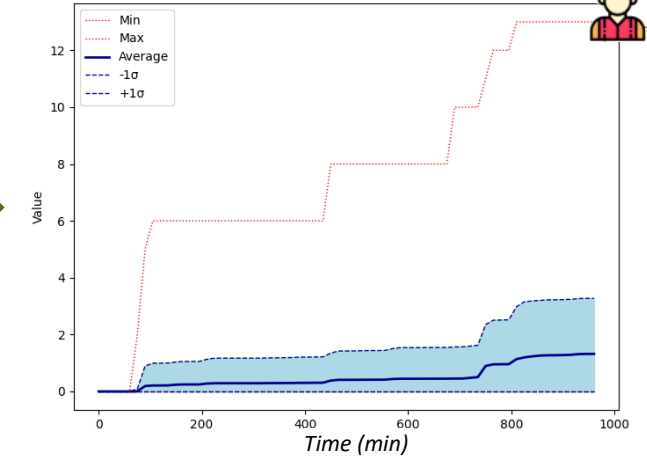
Wrappers: 2 units



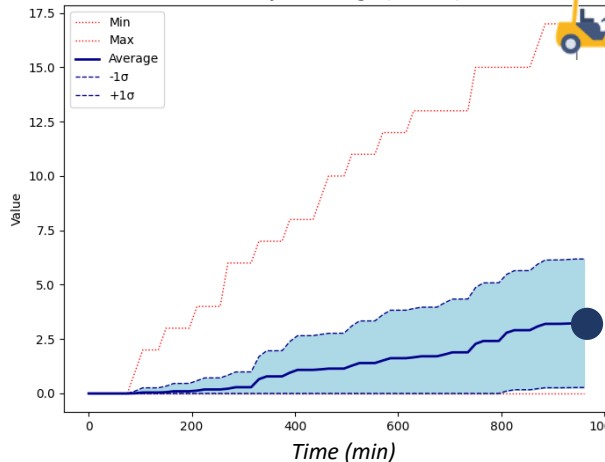
Operators shortage (events)



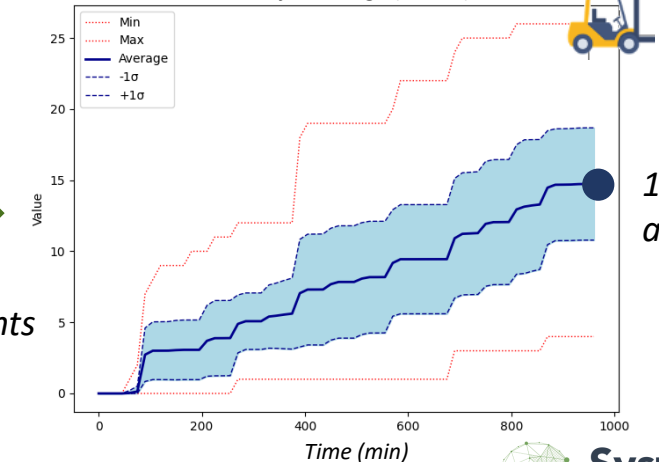
Operators shortage (events)



Forklift shortage (events)



Forklift shortage (events)



More industrial examples

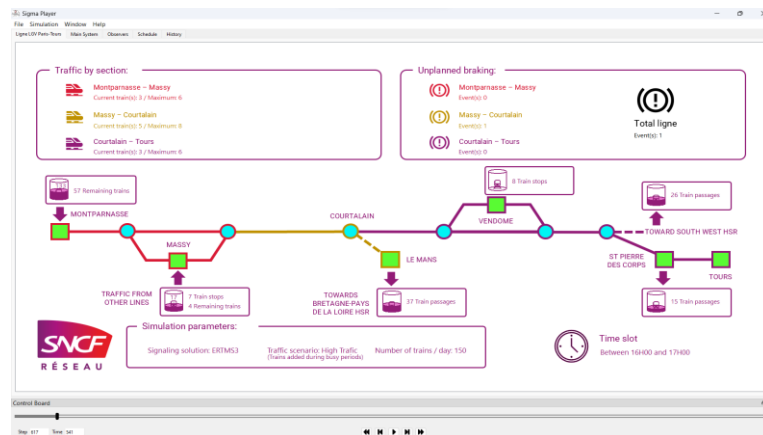


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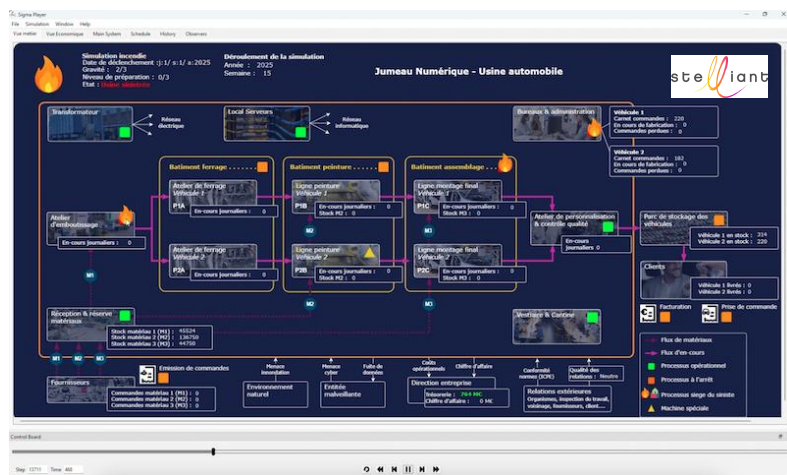


Other examples of actual systemic digital twins in the industry

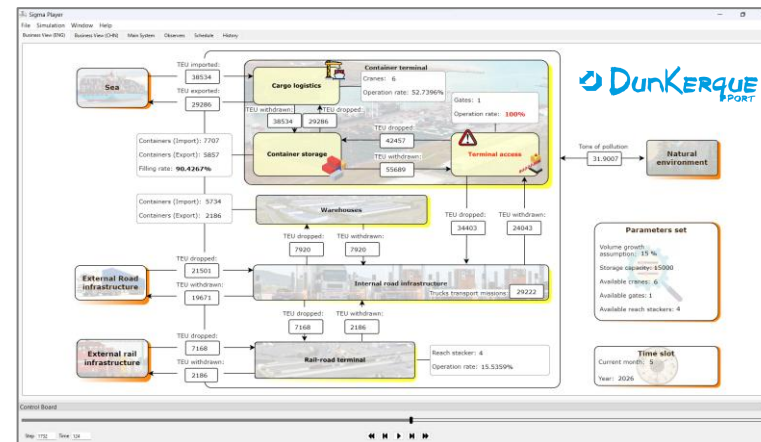
Performed thanks to our industrial customers & partners



Trade-off: comparison of 4 control-command railway architectures under 3 traffic growth hypotheses



Risk management: design of the best insurance strategy to cover industrial risks (fire, flood, cyber-attack)



Strategic decision: identification of nature and time of industrial investments under container traffic growth hypotheses

Systemic Intelligence is at your disposal for detailed information about these case studies, and / or to schedule a demo of WorldLab:

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