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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Systemic Intelligence

Sigma

WorldLab

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

l'X École Polytechnique Université Paris-Saclay

Spin-off - 2011

Partners

INCOSE • Systematic Paris Region Deep Tech Ecosystem • Dassault Systèmes • Tsinghua University

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

CESAM 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

Aeronautics

AIRBUS COMMERCIAL AIRCRAFTS, AVIC, COMAC, SAFRAN GROUP

+ CORAC, Daher Dassault Aviation

Automotive

NISSAN, MITSUBISHI MOTORS, GROUPE RENAULT, STELLANTIS, Valeo

+ Mitsubishi

Energy

EDF, framatome, Schneider Electric, slb

+ Rolls Royce, Technip

Defense & space

AIRBUS HELICOPTERS, arianeGROUP, DGA, SAFRAN ELECTRONICS & DEFENSE

+ Dassault Aviation, Kawasaki, Thalès

Civil engineering

GROUPE ADP, BOUYGUES CONSTRUCTION, OTIS, somfy

+ Eiffage, Saint-Gobain, Vinci

High-tech

HUAWEI, IDEMIA, SoftBank Robotics

+ A3BC, Dassault Systèmes, PTC

Innovation & services

bpifrance, dgac, Premier ministre – Secrétariat général pour l'investissement, stelliant, SystemX

+ Caisse des dépôts, Opéra National de Paris, Pôle Emploi

Logistics

Dunkerque Port, LA POSTE, fives

Mining

BHP, nordic mining, DEBSWANA – Mining diamonds, enriching the nation

Railway

ALSTOM, Eurail, RATP, SNCF RÉSEAU

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?

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

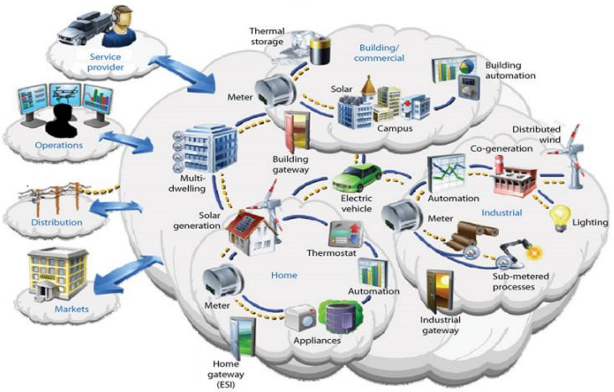
Optimization of industrial operations rely on many different types of **operational, tactical & strategic industrial decisions**

Why

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

AIRBUS Canada

Optimizing complex supply chains



Optimizing complex operations and maintenance

DunKerque PORT

LA POSTE

fives

NORDIC MINING

SNCF RÉSEAU

stellantis

Minimizing industrial risk

AIRBUS Canada

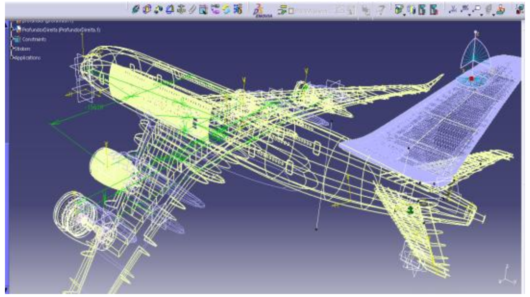
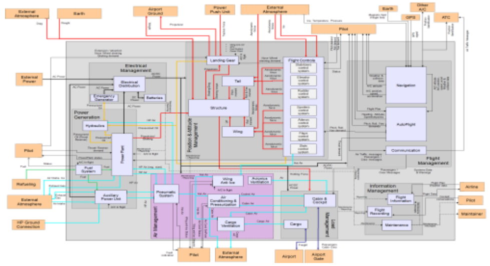
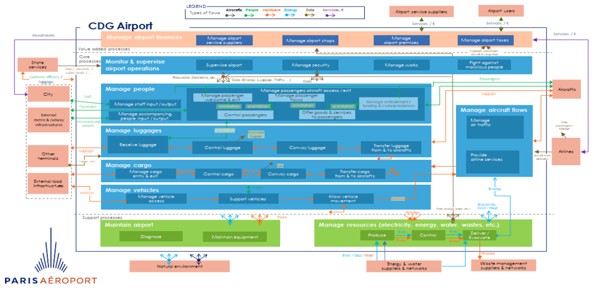
fives

Optimizing complex manufacturing

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)	 *Example: geometric model of an aircraft*	 *Example: geometric model of an airport*
Behaviour (what is doing the system)	 *Example: functional model of an aircraft*	 *Example: business processes of an airport*

Systemic digital twins

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

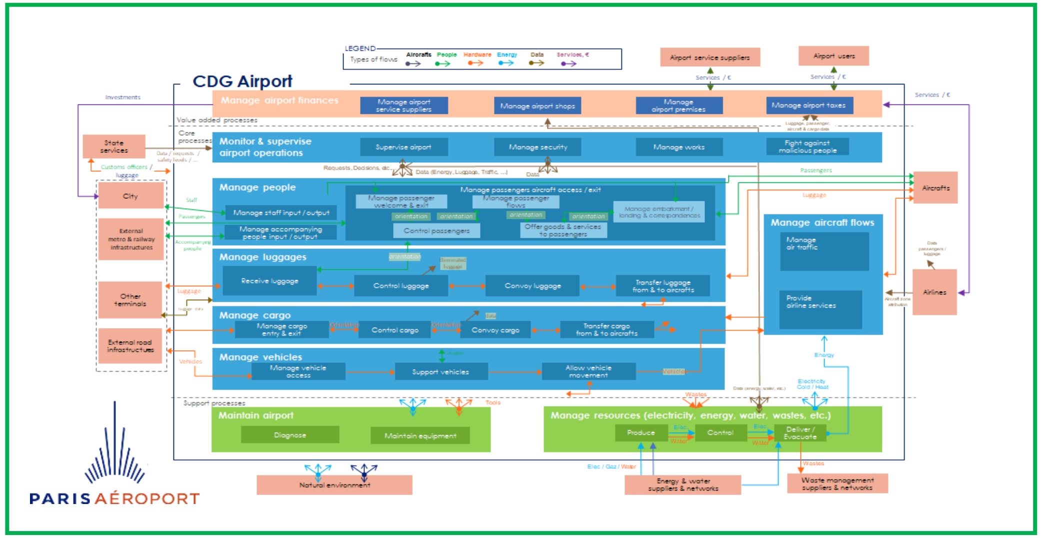
What

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

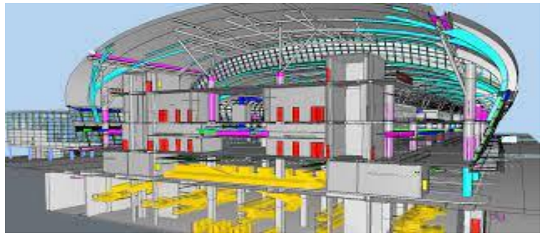
IOT & RFID infrastructure

Smart devices

Systemic digital twins



Business processes



Digital mock-ups

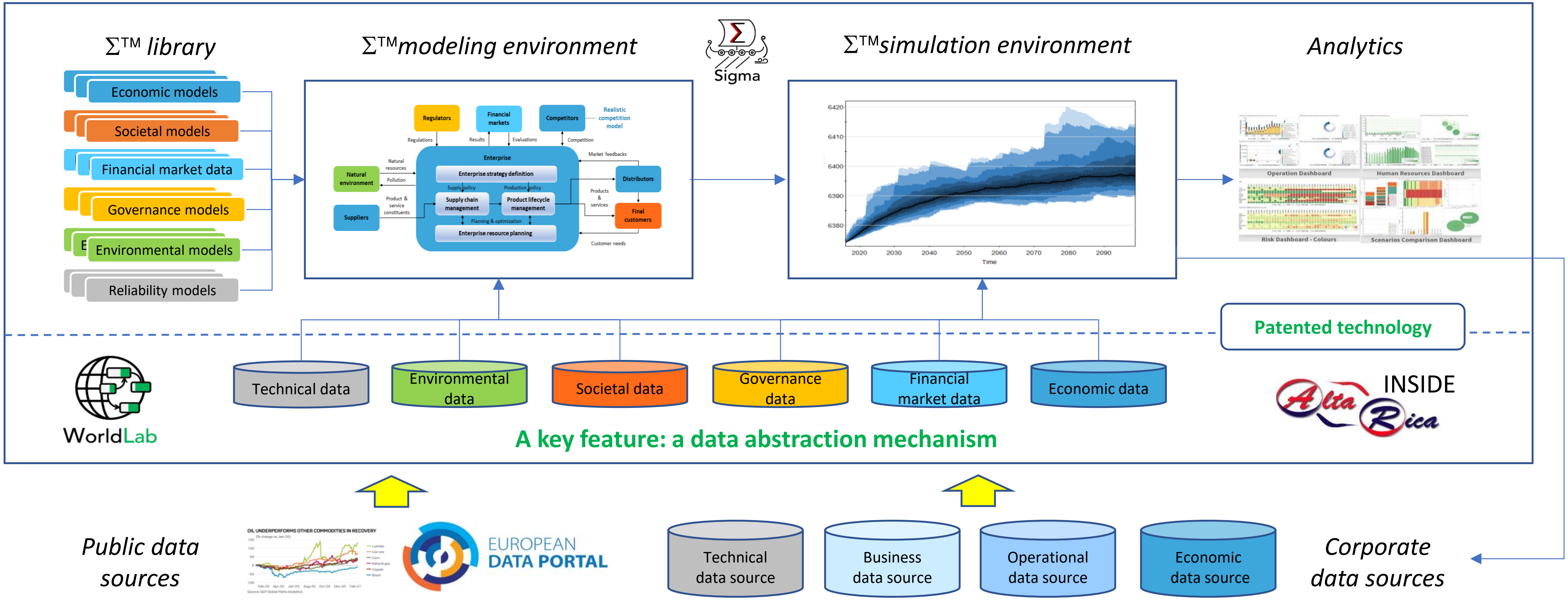
Building Information Modeling (BIM)

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

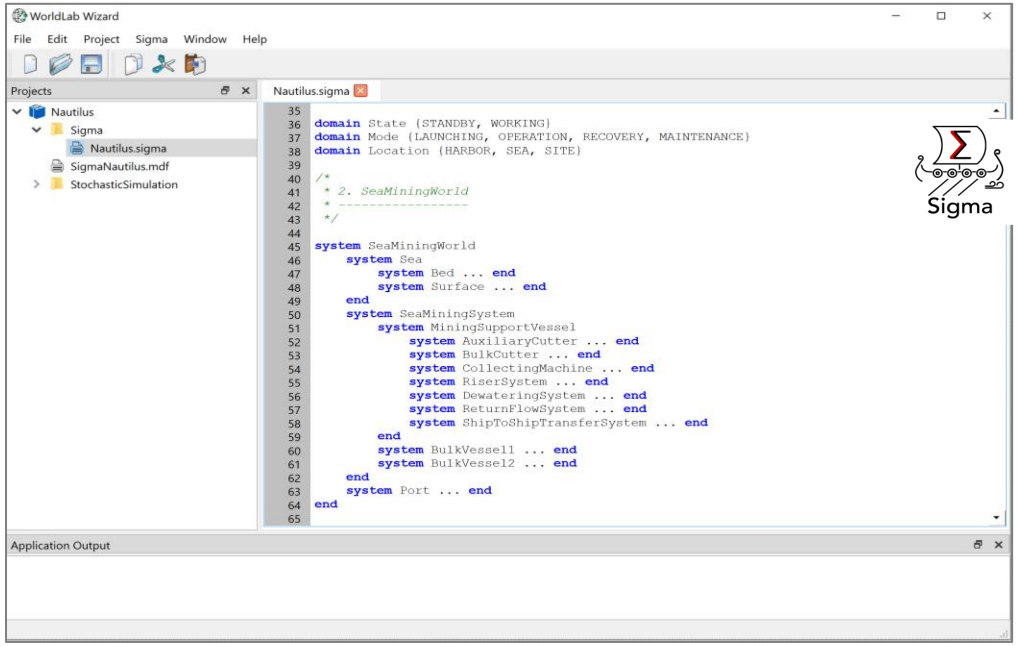
The technological scope of a systemic digital twin (1/2)



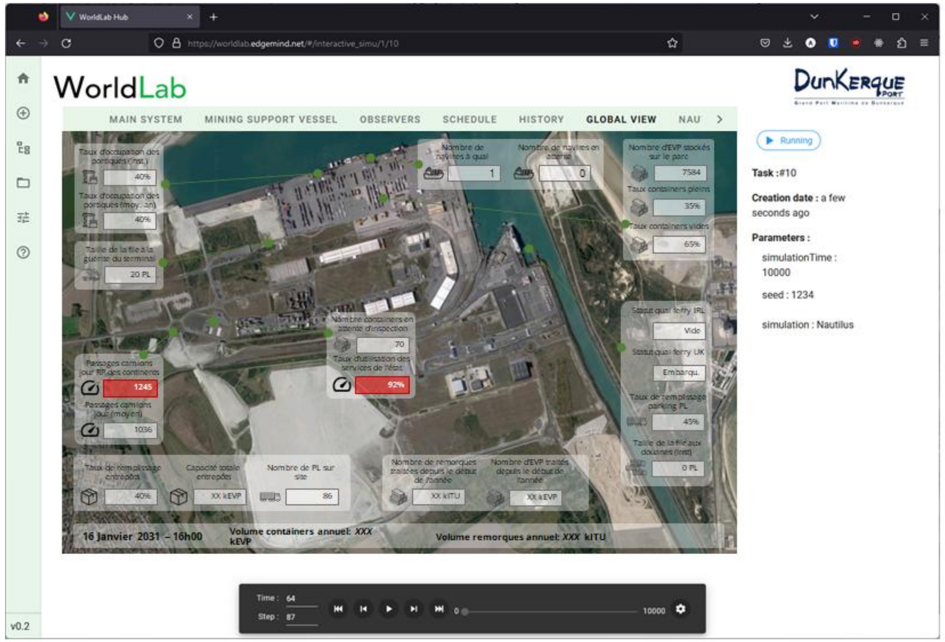
To support our vision, we developed the **WorldLab™ patented technology** – built on the **proven infrastructure of the AltaRica safety & reliability analysis tool**, developed by Antoine RAUZY during the last 20 years and industrially used in many industrial sectors – which is a **systemic intelligence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

Systemic Intelligence

How

The ΣTM modeling language at the core of WorldLab™ (1/2)

```
system World
  system Supplier
    int rawMaterial(init = 0);
  end
  system Producer
    int order(init = 0);
    int rawMaterial(init = 0);
    int product(init = 0);
  end
  system Consumer
    int order(init = 0);
    int product(init = 0);
  end
end
```

Specification of a hierarchy of systems in ΣTM

```
system World.Supplier
  int rawMaterial(init = 0);
  bool renewing(init = false);
end

activity World.Supplier.RenewRawMaterialStock
  trigger:
    return rawMaterial<=1000 and not renewing;
  start:
    renewing = true;
  completion: {
    renewing = false;
    rawMaterial += 100;
    }
  duration:
    return 30;
end
```

- `return rawMaterial<=1000 and not renewing;` ← *Condition that triggers the activity*
- `renewing = true;` ← *What shall be done when the activity starts*
- `renewing = false; rawMaterial += 100;` ← *What shall be done when the activity stops*
- `return 30;` ← *Duration of the activity (in units of time)*

Specification of a business process – as an activity – in ΣTM

The **ΣTM 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™ modeling language at the core of WorldLab™ (2/2)

```
activity World.Consumer.ConsumeProduct
  trigger:
    return product>=1000 and not consuming;
  start:
    consuming = true;
  completion: {
    consuming = false;
    product -= uniformDeviate(1, 2.5);
    }
  duration:
    return 1;
end
```

Example of a stochastic quantity with explicit probabilistic distribution

```
activity World.Consumer.ConsumeProduct
  trigger:
    return product>=1000 and not consuming;
  start:
    consuming = true;
  completion: {
    consuming = false;
    product -= 1;
    }
  duration:
    return triangularDeviate(1, 5, 2);
end
```

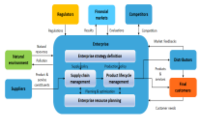
Example of a stochastic duration with explicit probabilistic distribution

Stochastic behaviors can be captured within Σ™ in two different ways, either via variables manipulated by **activities** or via **durations**. One can express in Σ™ 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

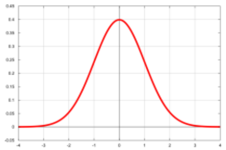
The key unique features of WorldLab™

- **Simplicity & Maintainability –** A systemic digital twin is specified in the **object-oriented modeling language Σ™** 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.

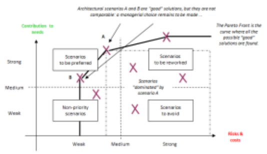


- **Heterogeneity –** A systemic digital twin can integrate **various heterogeneous features**, such as technical functions, maintenance policies, societal behaviors, financial market evolutions, regulatory strategies or meteorologic conditions, into a **single unique systemic model**, allowing to analyze 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.



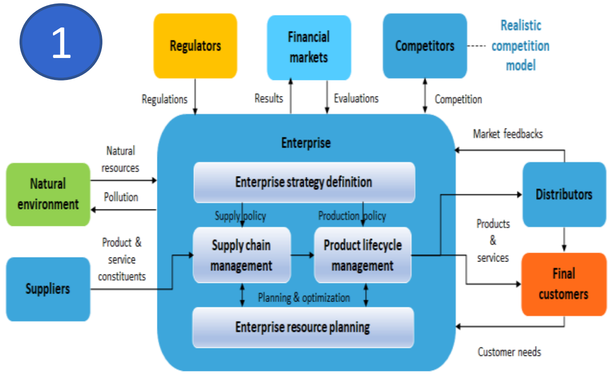
- **Hazards – Hazards** can be effectively captured in a systemic digital twin: each variable specified in the Σ™ modeling language can be a random variable with a specific probability distribution – either explicit or pragmatic – allowing to capture **random quantities & random delays** and to manage **stochastic simulations** for a given industrial system.

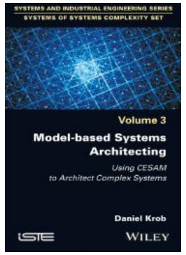


- **Scenarios Evaluation & Prioritization –** The WorldLab™ platform proposes dedicated features for **evaluating & prioritizing business evolution scenarios** which allow to achieve **multi-criteria optimization**, e.g. maximizing production when minimizing delays & energy consumption, with respect to a given industrial system.

In practice

Systemic digital twins do connect MBSE to simulation





MBSE model of an industrial system

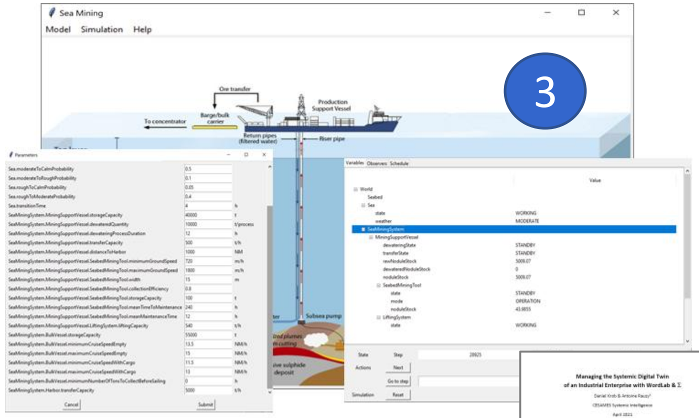
```
system World
  system Supplier ... end
  system Producer ... end
  system Consumer ... end
end

system World.Supplier
  int rawMaterial(init = 0);
end

system World.Producer
  int order(init = 0);
  int rawMaterial(init = 0);
  int product(init = 0);
end

system World.Consumer
  int product(init = 0);
end
```

2

Sigma

ΣTM model of an industrial system

WorldLab



Systemic digital twin of an Industrial system

Principle of the development of a systemic digital twin of an industrial system with ΣTM 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 **ΣTM formal modeling language**.

Systemic Intelligence

A case study: design of an automated warehouse

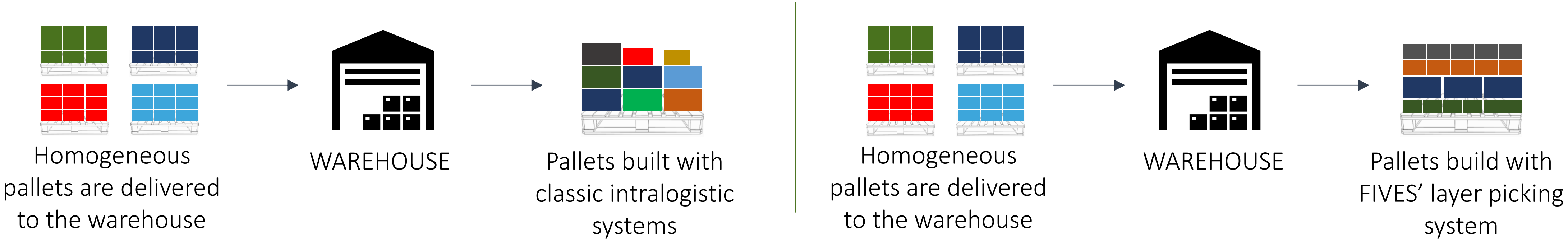
Systemic Intelligence

A case study: the design of an automated warehouse

A bit of context

fives

- **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.



Systemic Intelligence

A case study: the design of an automated warehouse

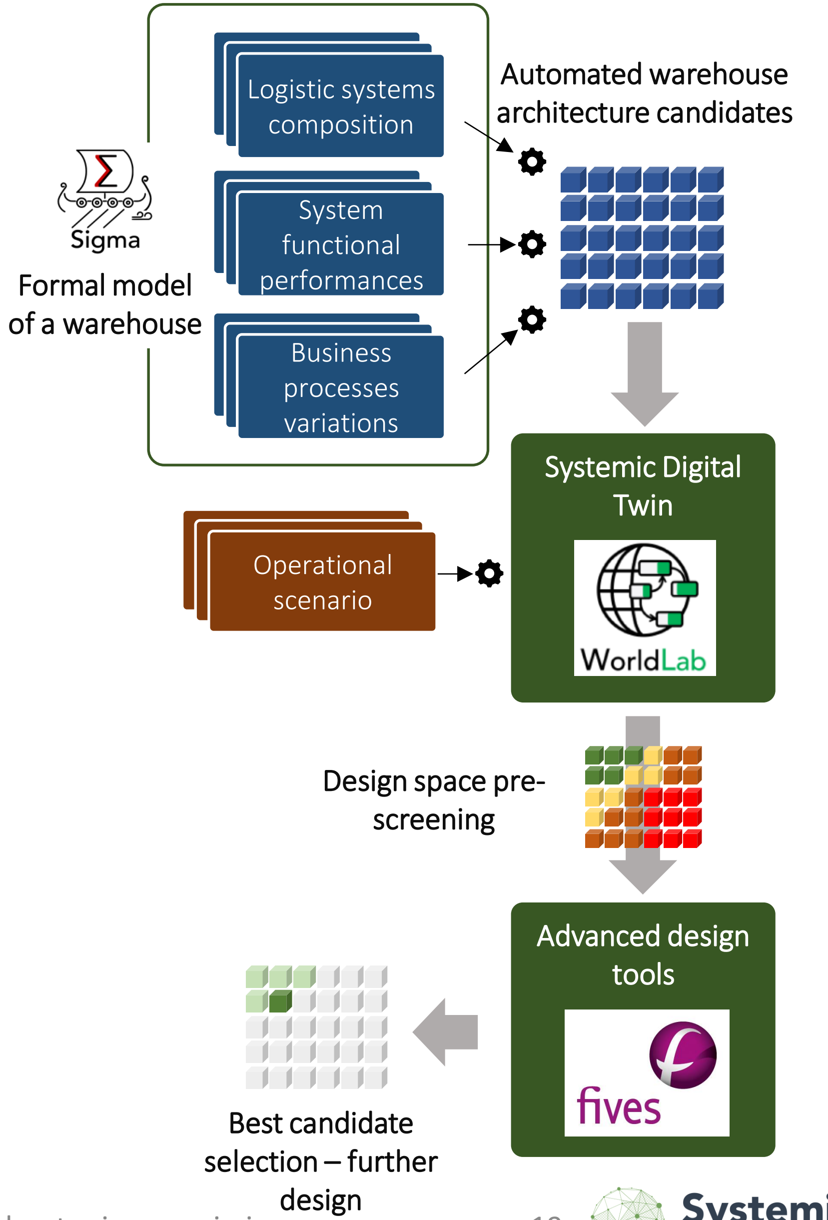
Why a systemic digital twin ?

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

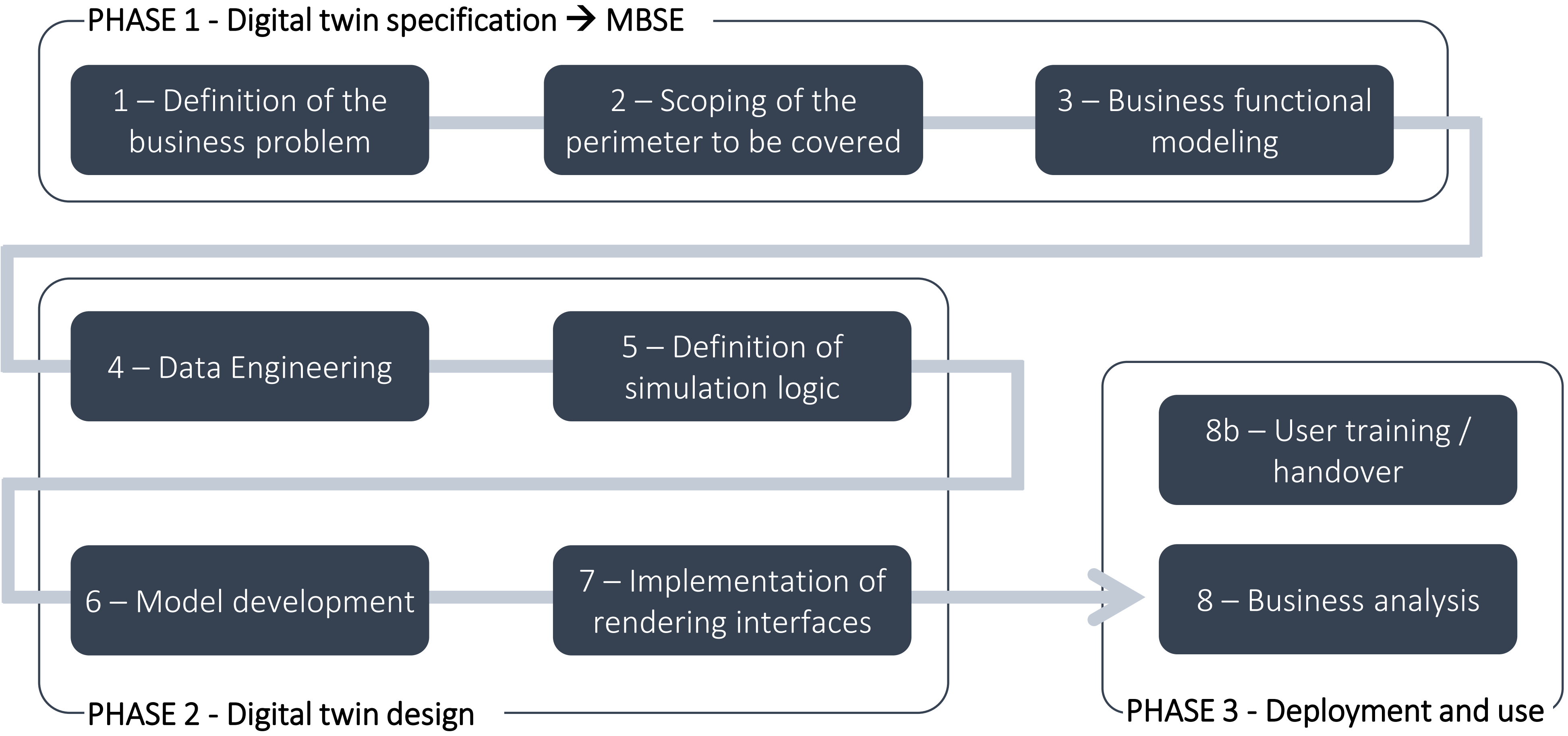
FIVES needed a tool they can **use in preliminary design**, able to conduct thorough **design space exploration** at a **macroscopic level**:

- **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

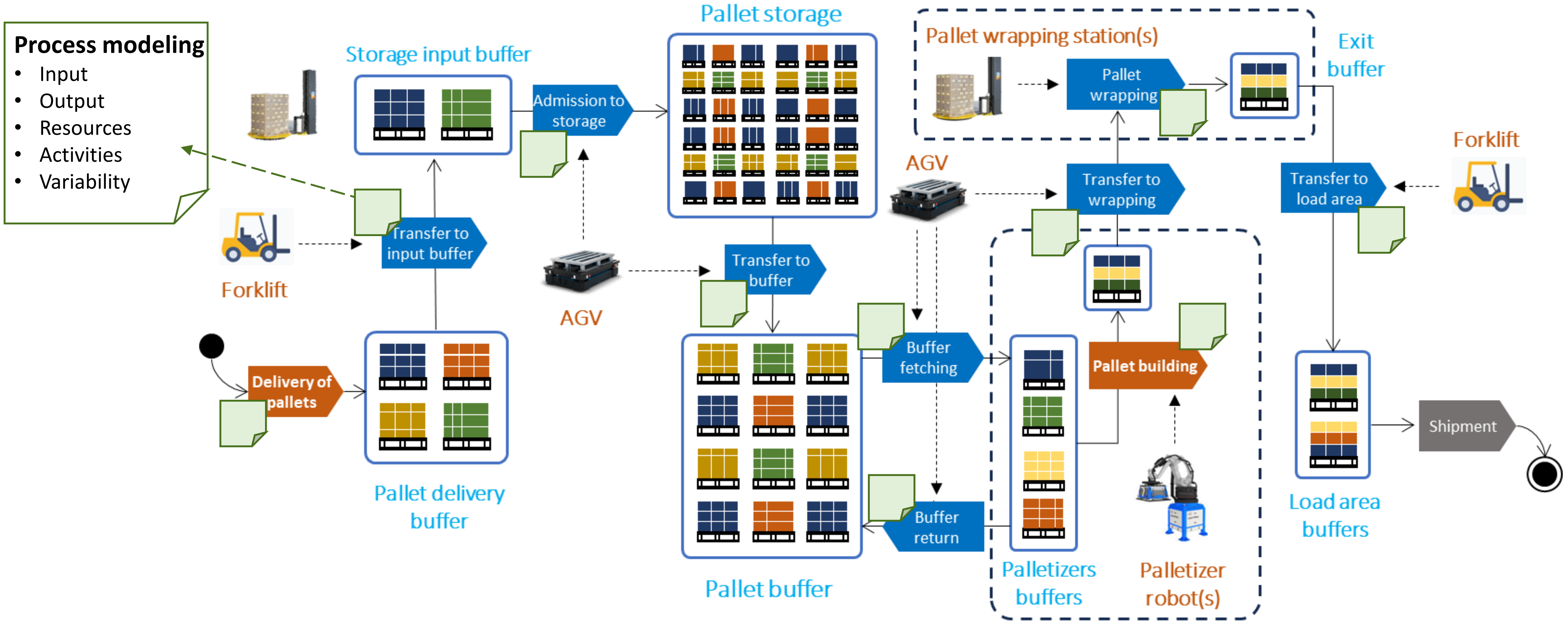
For a predictive and fixed intensity of warehouse activities, to maximize the utilization rate of costly assets and minimize buffer inflation

- 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 ?

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

Phase 1: Digital twin specification

Scoping of the perimeter to be covered & business process modeling



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 ΣTM**.

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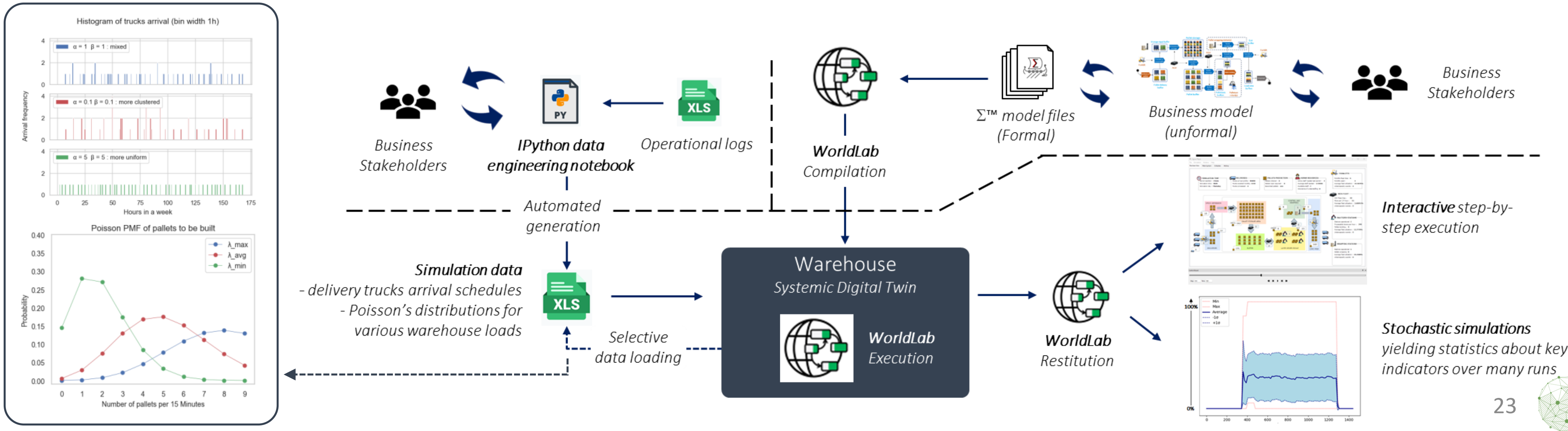
Phase 2: Digital twin design

Digital twin model build & simulation logic

Thanks to its **dedicated primitives**, Σ™ allows to build a formal model **aligned with the MBSE model of the system of interest** derived through phase 1.

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

- The automated warehouse is exposed to **externally driven logistic flows**: deliveries and customers' demand
- These flows are:
  - Of variable intensity : from one scenario to another, and throughout the simulated day.
  - Derived from **“real life” warehouse data** that have been **mathematically processed**
- Simulations are **run many times**, to assess how the warehouse performs **for a given architecture**, through the computation of **statistics for key metrics** taking into account the **stochasticity** of modelled processes



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Phase 2: Digital twin design

Σ™ 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**

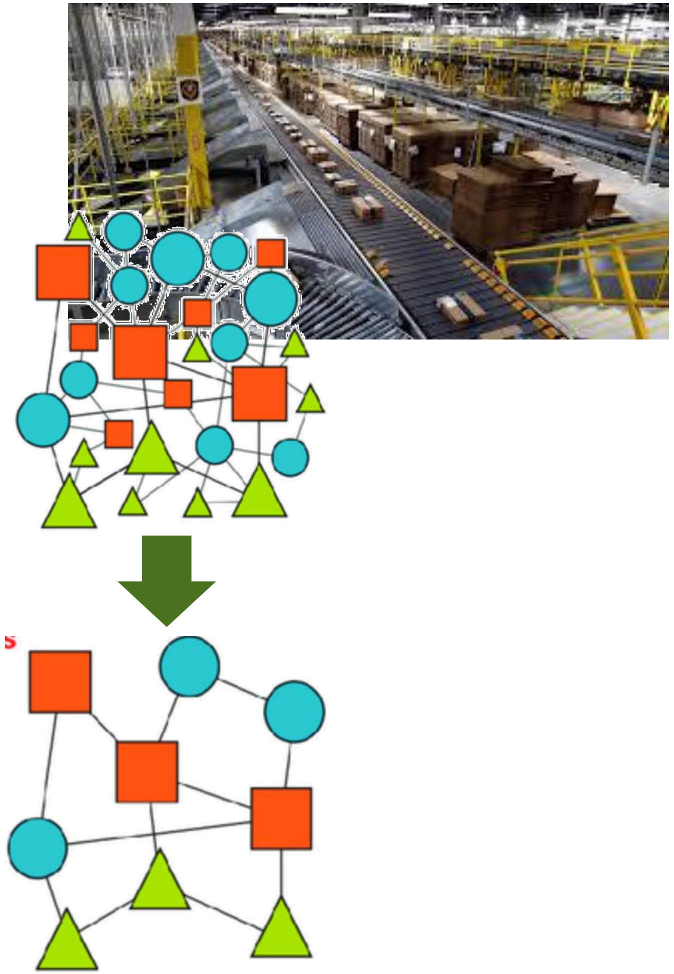
However, a day's worth of operations must be simulable in a **very short amount of time** :

- 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 **capacitary 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.

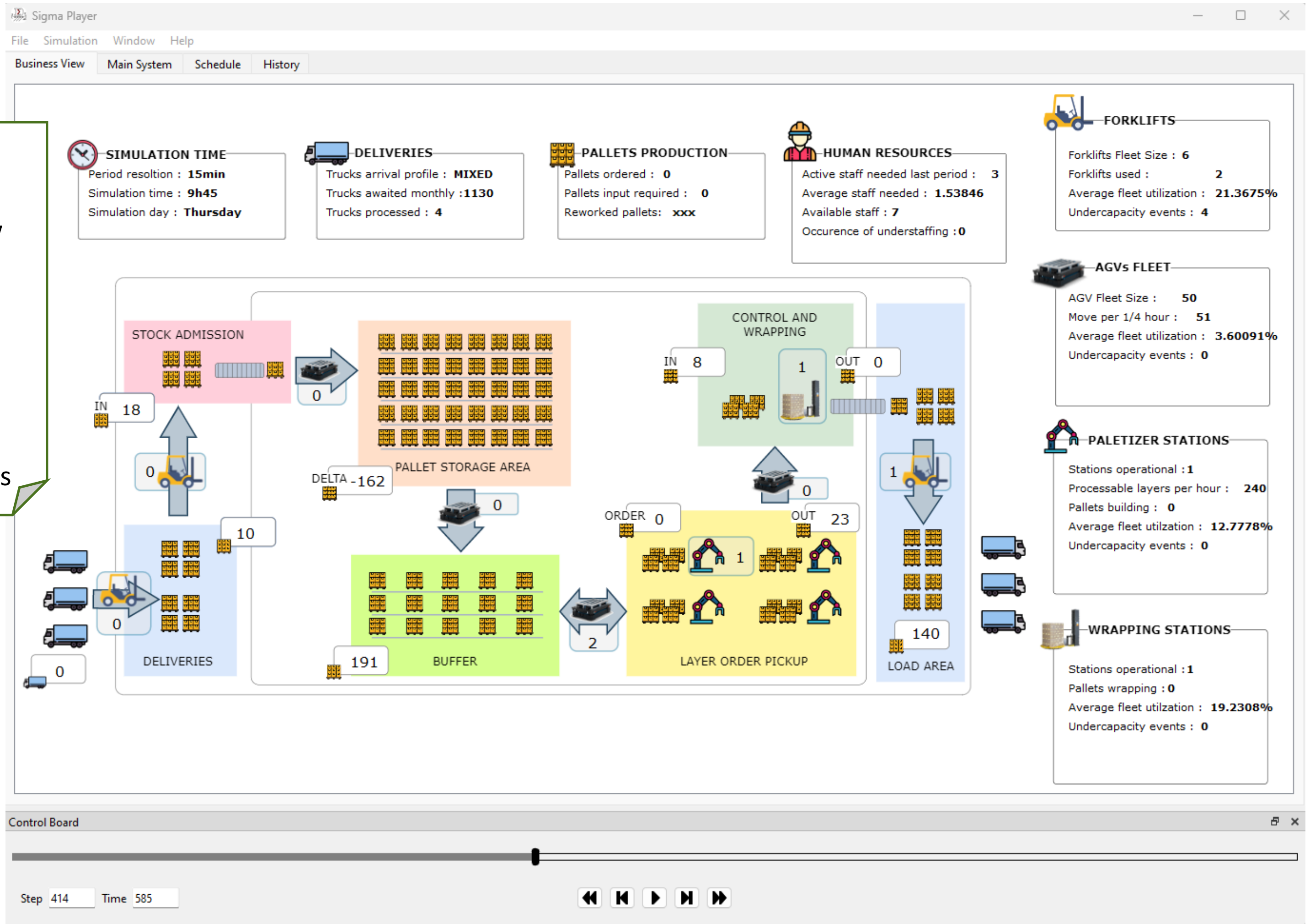


Phase 2: Digital twin design

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

Deliveries: uniform

Pallets : 2 700 / week avg

Palletizers: 8 units

HR: 7 workers

Forklifts: 6 units

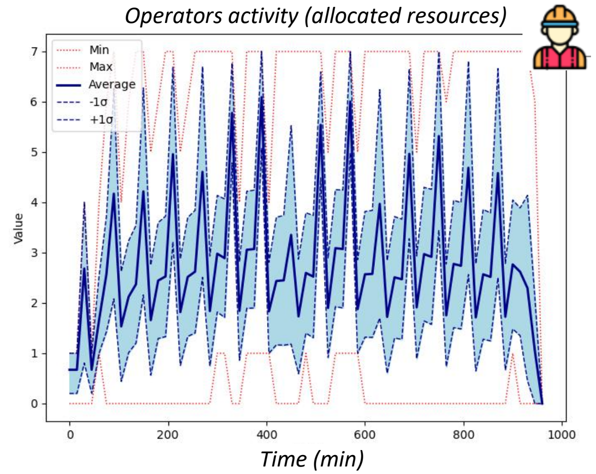
AMR: 18 units

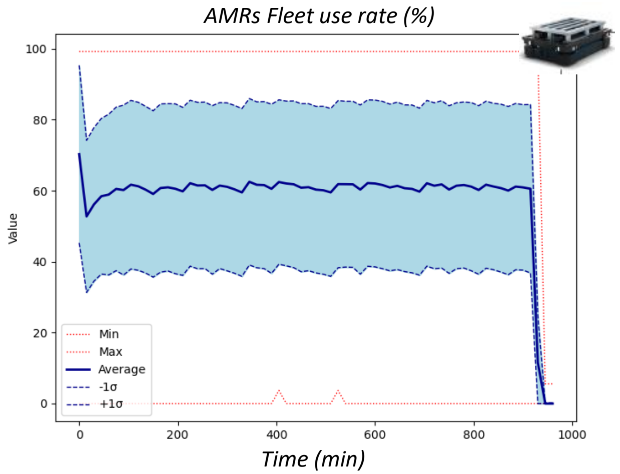
Wrappers: 2 units

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.

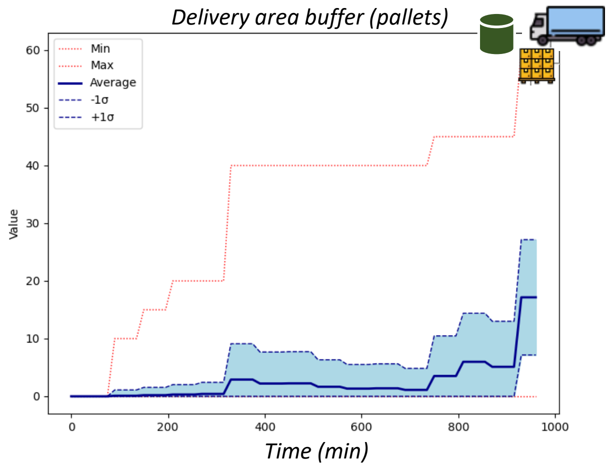
- The load rate of human resources is around 40%, and AGVs is 60%. **Peak capacity is rarely reached**.
- There is **no accumulation in key buffers**: the delivery area, and the palletizers orders backlog.

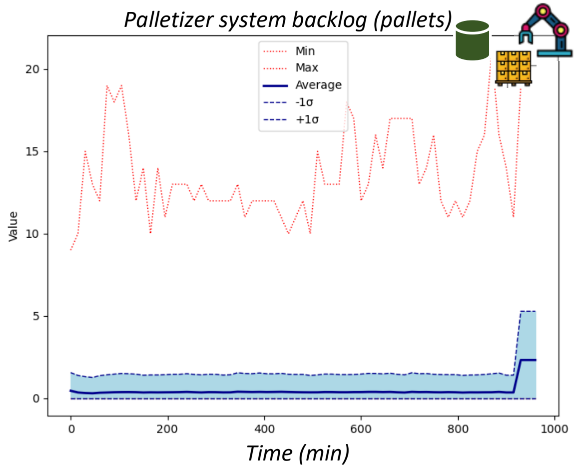




Q1 : How well will this warehouse respond in case of a high intensity event (ie. black friday) ?

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





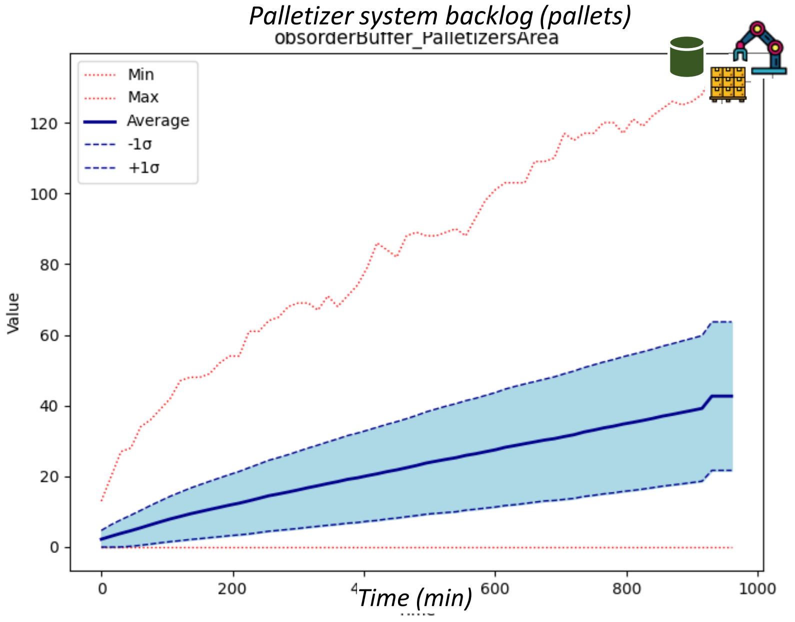
Phase 3: Deployment and use

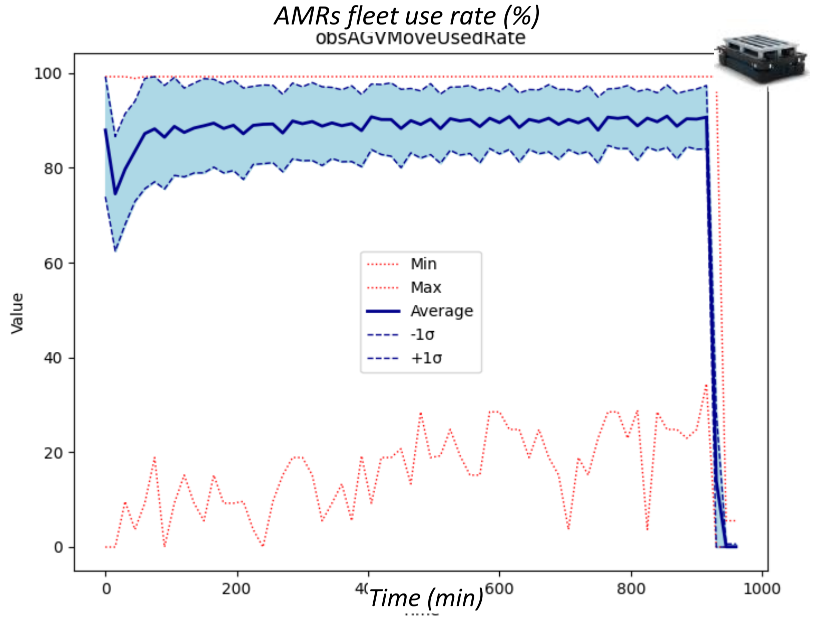
Use case 1 – Q1 : findings & conclusion (1/2)

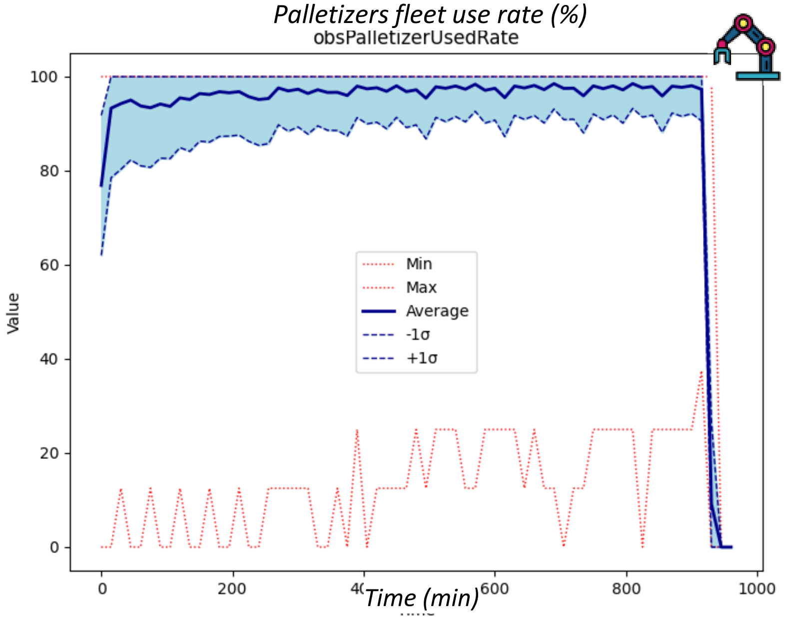
Deliveries: uniform **Pallets** : **4 600 / week avg** **Palletizers**: 8 units

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 solicitated too (mean + std dev ~95%)

Phase 3: Deployment and use

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

Deliveries: uniform

Pallets : **4 600 / week avg**

Palletizers: 8 units

HR: 7 workers

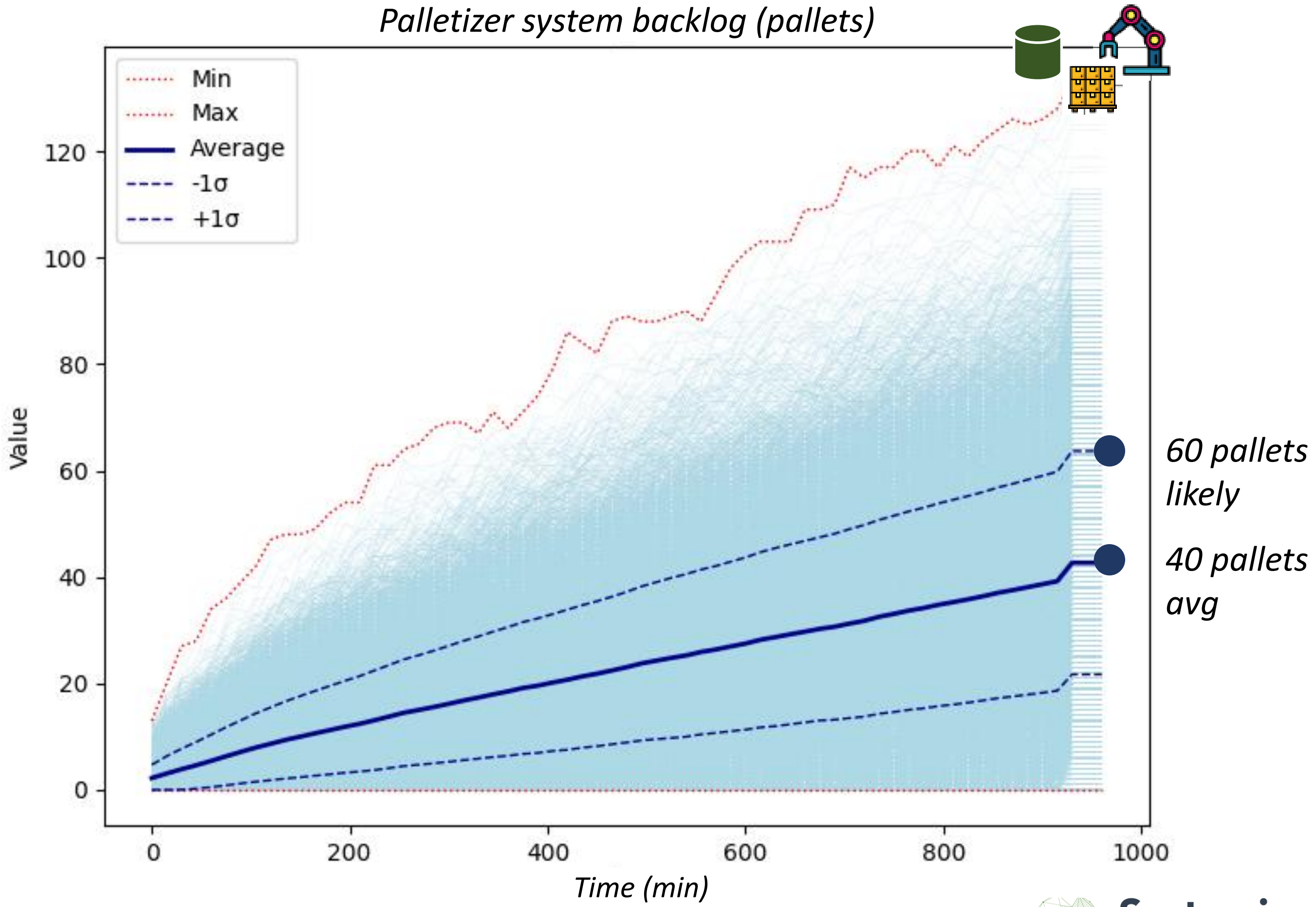
Forklifts: 6 units

AMR: 18 units

Wrappers: 2 units

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

- 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 !



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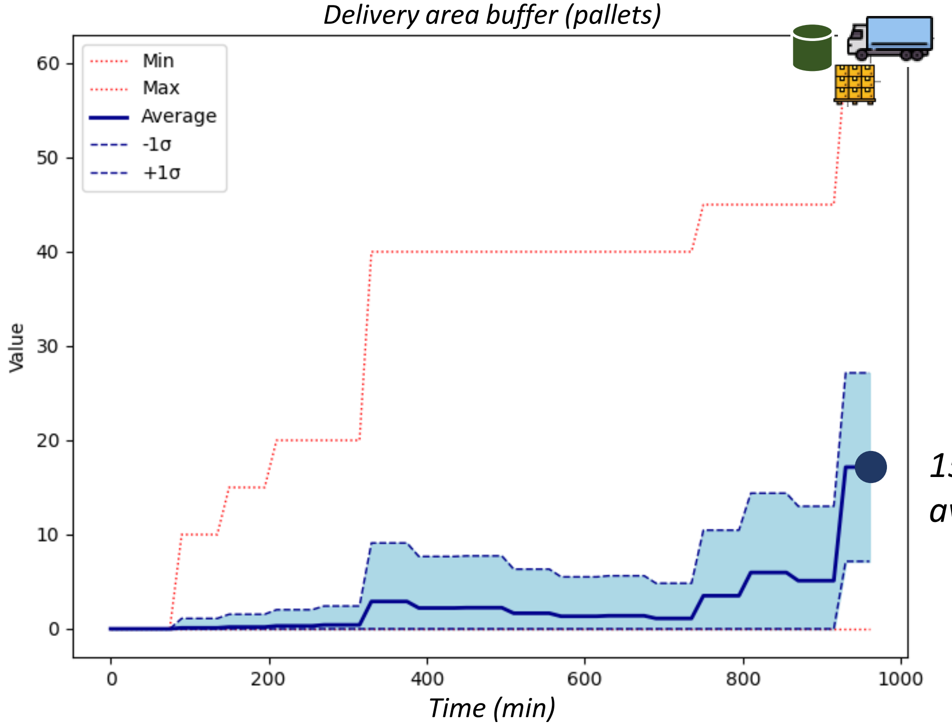
Phase 3: Deployment and use

Use case 1 – Q2 : Findings & conclusion

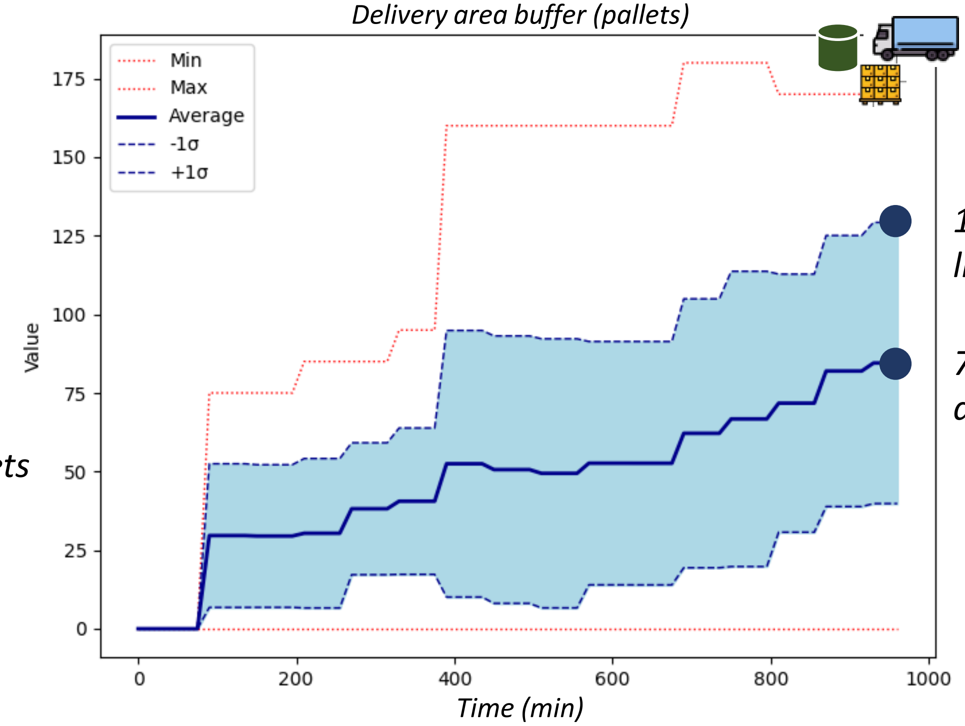
Deliveries: clustered **Pallets** : 2 700 / week avg **Palletizers**: 8 units

HR: 7 workers **Forklifts**: 6 units **AMR**: 18 units **Wrappers**: 2 units

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



15 pallets avg



125 pallets likely

75 pallets avg

- 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

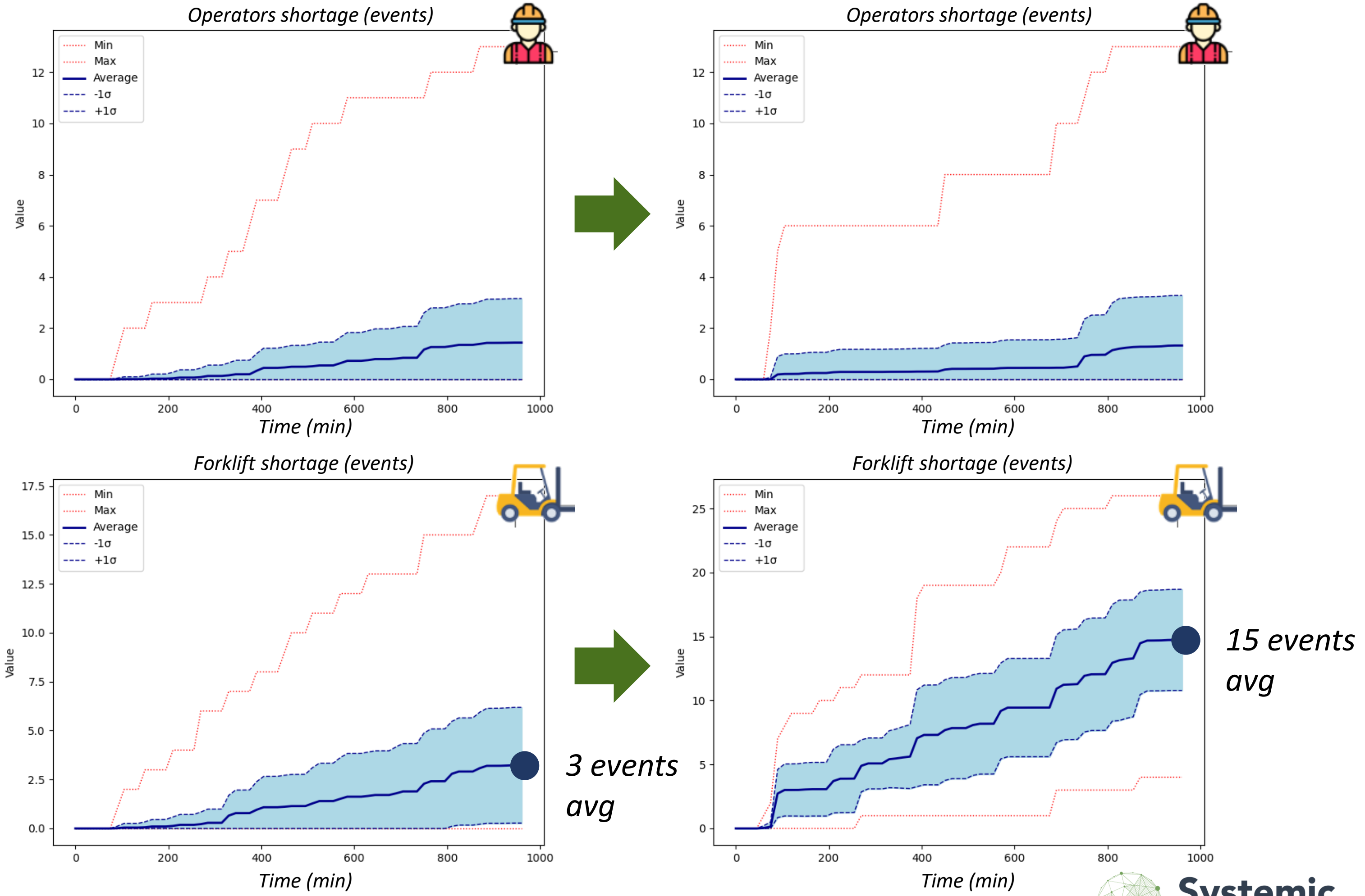
Use case 1 – Q2 : Findings & conclusion

Deliveries: clustered | **Pallets** : 2 700 / week avg | **Palletizers**: 8 units

HR: 7 workers | **Forklifts**: 6 units | **AMR**: 18 units | **Wrappers**: 2 units

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



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More industrial examples

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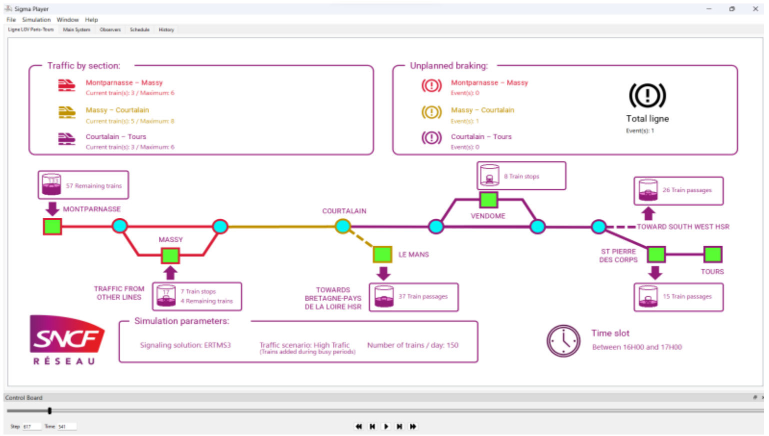
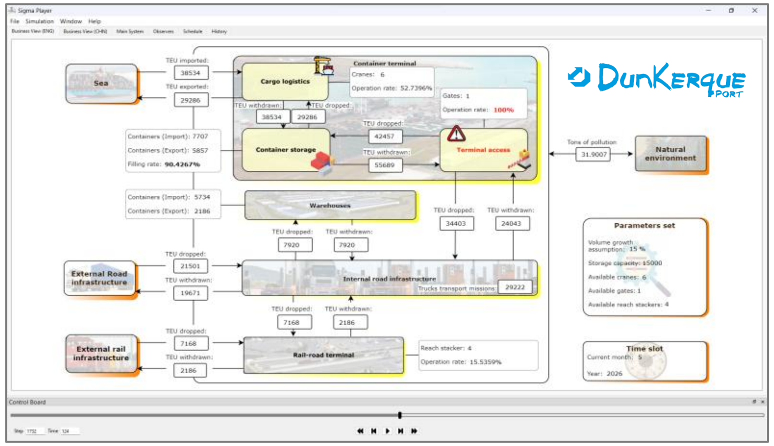
Other examples of actual systemic digital twins in the industry

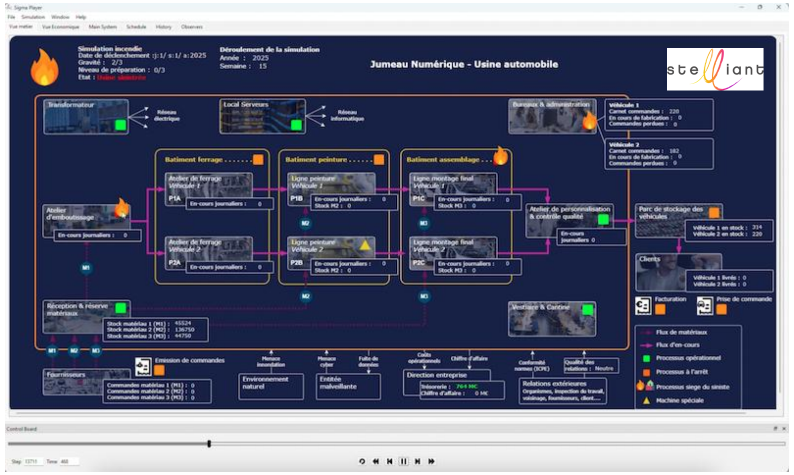
Performed thanks to our industrial customers & partners



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



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



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

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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