Modeling & simulation of industrial systems with systemic digital twins

WorldLab

Sigma

Daniel KROB (INCOSE Fellow)

June 2023

Systemic Intelligence

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Agenda

1. **Systemic Intelligence Group**
2. Modeling & simulation of industrial systems
3. Systemic digital twins of industrial systems
4. An illustrative example: a submarine mine
5. Questions & answers

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Systemic Intelligence in a nutshell

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
Modeling expertise
Systemic digital twins
Coaching & training

Team
30
architects

Income
7 M€
2022

Offices
Paris
Toulouse
Shanghai

Creation
Spin-off - 2011

Partners
INCOSE · Systematic Paris Region Deep Tech Ecosystem · Dassault Systèmes

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 part of CESAMES group, a **spin-off** of the industrial chair “Engineering of complex systems” of Ecole Polytechnique which is specialized in **systems architecting & engineering**, a domain that proposes modeling & simulation techniques that aims at better mastering industrial complexity. We disseminated **innovative methods & tools** in this area for the last 10 years within various industries (aeronautics, automotive, construction, defense, energy, high tech, railway, space), mainly in China, France, Germany and Japan.

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Systemic Intelligence – Our customers

Aeronautics

+ CORAC, Daher Dassault Aviation

Automotive

+ Mitsubishi

Energy

+ Rolls Royce, Technip

Defense & space

+ Dassault Aviation, Kawasaki, Thalès

Construction

+ Eiffage, Saint-Gobain, Vinci

High tech

+ A3BC, Dassault Systèmes, PTC

Innovation

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

Logistics

Mining

Railway

Our current ecosystem of industrial customers

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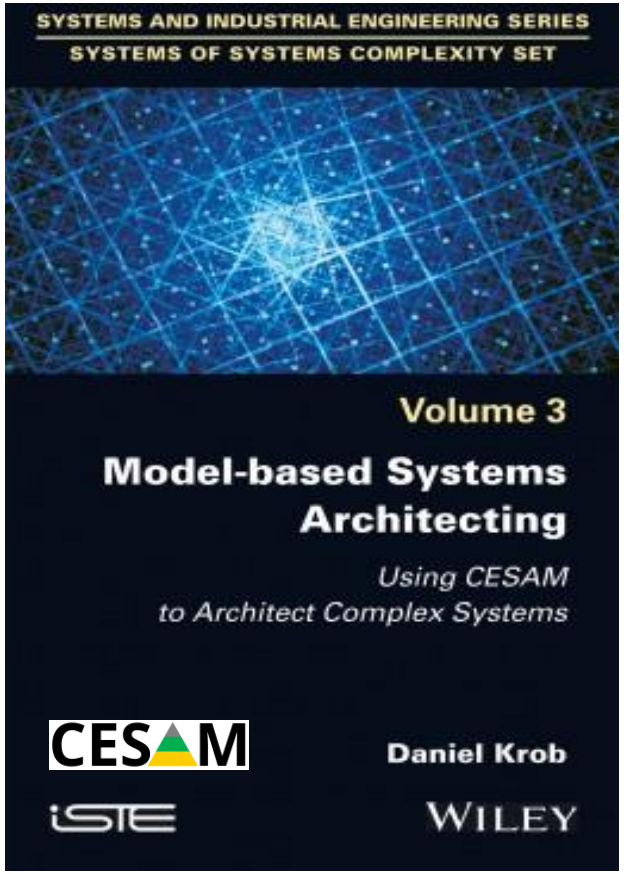
Systemic Intelligence – The scientific pillars of systemic digital twins



A Guided Tour of the Systemic Modeling Language Σ

Daniel Krob and Antoine Rauzy

February 22, 2022

Sigma

Abstract

Σ is both a language and a method for describing and studying the dynamics of complex technical and socio-technical systems and their environment. It makes it possible to implement computer simulations, to assess key performance indicators by means of these simulations, to play "what-if" scenarios and to apply optimization techniques. In a word, the framework we propose here supports the design of systemic digital twins of complex technical systems.

This article aims both at providing a guided tour of the Σ modeling framework and at illustrating its use by means of examples.

1 Introduction

Our world runs on increasingly complex technical systems. Engineers face a critical challenge in designing, managing, and optimizing these systems. One of the key issues is that traditional development methods, based on local optimization and silo-ed engineering disciplines do not suffice anymore (de Weck, Roos, and Magee 2011). One needs a holistic perspective on systems and their environment, encompassing technical, organizational, economical, environmental and regulatory opportunities and constraints. Systems engineering aims at providing concepts, methods and tools to support such an approach (Walden et al. 2015).

To tackle the complexity of systems, engineers more and more on computer models and simulations. By designing these digital twins of the systems, they pursue two main objectives: first, to better understand the systems and to ensure that stakeholders share a common understanding of the problems at stake; second, to assess key performance indicators without having to perform physical experiments, which would be too costly, or simply impossible.

Models are already pervasive in most of the engineering disciplines like mechanical, electrical, or reliability engineering. As of today, their introduction into systems engineering is still an on going process and the subject of active researches and developments. Modeling technologies to be applied are still debated. One of the main difficulties is to capture the key features of the system under study while staying at the suitable level of abstraction. Another difficulty is to integrate in the models the heterogeneous characteristics of systems.

The Σ modeling framework aims at providing a generic, mathematically sound and computationally efficient, solution to these difficulties. It relies on two pillars. First, one describes the architecture of the system under study, i.e. the system is decomposed into subsystems. These subsystems can be themselves further decomposed until the suitable granularity is reached. The state of each subsystem is described by means of discrete (symbolic) and continuous variables. Second, one describes activities performed by subsystems. Activities are guarded, i.e. they are performed when a certain condition on the state of the system is satisfied. They take time. This time may be deterministic or stochastic. Finally, they modify twice the state of the system. First at their beginning, to book the resources they need. Second at their completion, to release these resources and to describe their effect on the state of the system. Activities can not only modify the values of variables, but also create, move and delete components.

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Managing the Systemic Digital Twin
of an Industrial Enterprise with WordLab & Σ

Daniel Krob & Antoine Rauzy[1]

CESAMES Systemic Intelligence

April 2021

WorldLab

Table of contents

Our systemic digital twins rely on three main innovative pillars: 1) the CESAM system architecting method used in the **design phase**, 2) the new systemic specification language Σ™ used in the **beginning of the development phase**, 3) the WorldLab™ platform that supports the **end of the development phase** and the **use phase**.

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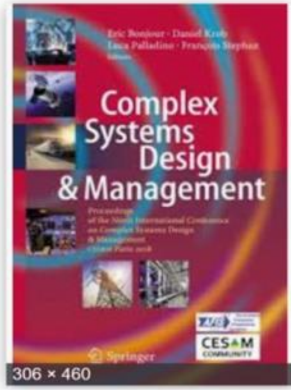
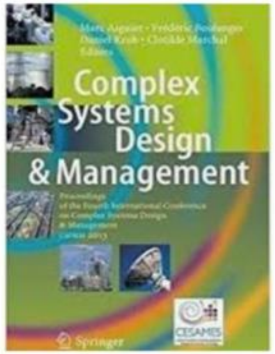
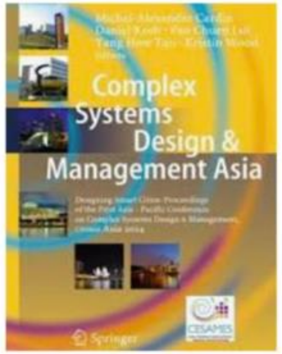
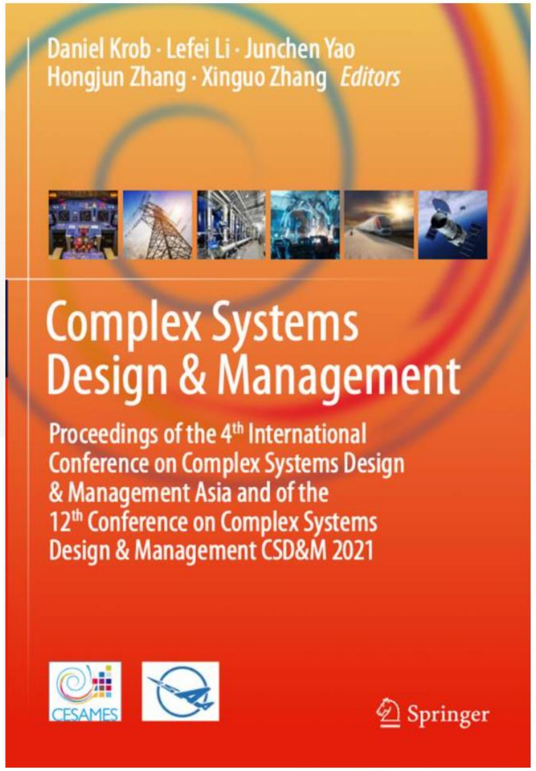
Systemic Intelligence – Our academic & professional network









Our network is especially animated through the **academic & professional events** that we are regularly organizing in France and Asia, the most important one being the international conference on **Complex Systems Design & Management** (CSD&M), that we already organized each year in Beijing, Paris and Singapore during the last 12 years.

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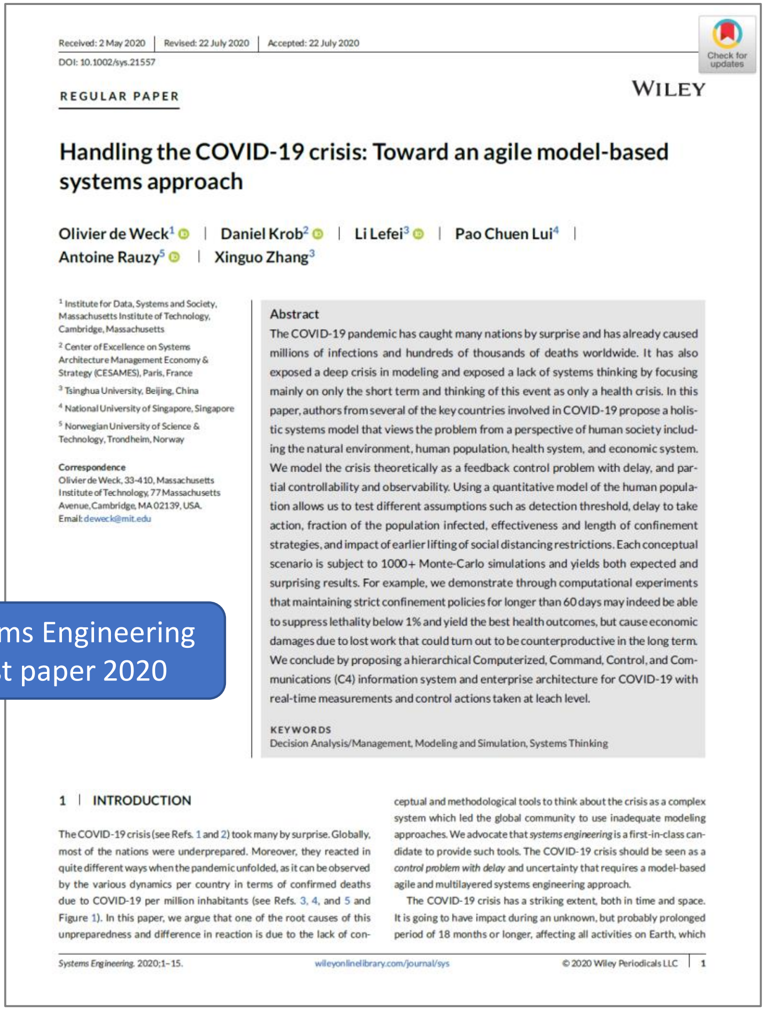
Systemic Intelligence – The starting point of our journey



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REGULAR PAPER

WILEY

Handling the COVID-19 crisis: Toward an agile model-based systems approach

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Abstract

The COVID-19 pandemic has caught many nations by surprise and has already caused millions of infections and hundreds of thousands of deaths worldwide. It has also exposed a deep crisis in modeling and exposed a lack of systems thinking by focusing mainly on only the short term and thinking of this event as only a health crisis. In this paper, authors from several of the key countries involved in COVID-19 propose a holistic systems model that views the problem from a perspective of human society including the natural environment, human population, health system, and economic system. We model the crisis theoretically as a feedback control problem with delay, and partial controllability and observability. Using a quantitative model of the human population allows us to test different assumptions such as detection threshold, delay to take action, fraction of the population infected, effectiveness and length of confinement strategies, and impact of earlier lifting of social distancing restrictions. Each conceptual scenario is subject to 1000+ Monte-Carlo simulations and yields both expected and surprising results. For example, we demonstrate through computational experiments that maintaining strict confinement policies for longer than 60 days may indeed be able to suppress lethality below 1% and yield the best health outcomes, but cause economic damages due to lost work that could turn out to be counterproductive in the long term. We conclude by proposing a hierarchical Computerized, Command, Control, and Communications (C4) information system and enterprise architecture for COVID-19 with real-time measurements and control actions taken at leach level.

KEYWORDS
Decision Analysis/Management, Modeling and Simulation, Systems Thinking

1 | INTRODUCTION

The COVID-19 crisis (see Refs. 1 and 2) took many by surprise. Globally, most of the nations were underprepared. Moreover, they reacted in quite different ways when the pandemic unfolded, as it can be observed by the various dynamics per country in terms of confirmed deaths due to COVID-19 per million inhabitants (see Refs. 3, 4, and 5 and Figure 1). In this paper, we argue that one of the root causes of this unpreparedness and difference in reaction is due to the lack of conceptual and methodological tools to think about the crisis as a complex system which led the global community to use inadequate modeling approaches. We advocate that *systems engineering* is a first-in-class candidate to provide such tools. The COVID-19 crisis should be seen as a *control problem with delay* and uncertainty that requires a model-based agile and multilayered systems engineering approach.

The COVID-19 crisis has a striking extent, both in time and space. It is going to have impact during an unknown, but probably prolonged period of 18 months or longer, affecting all activities on Earth, which

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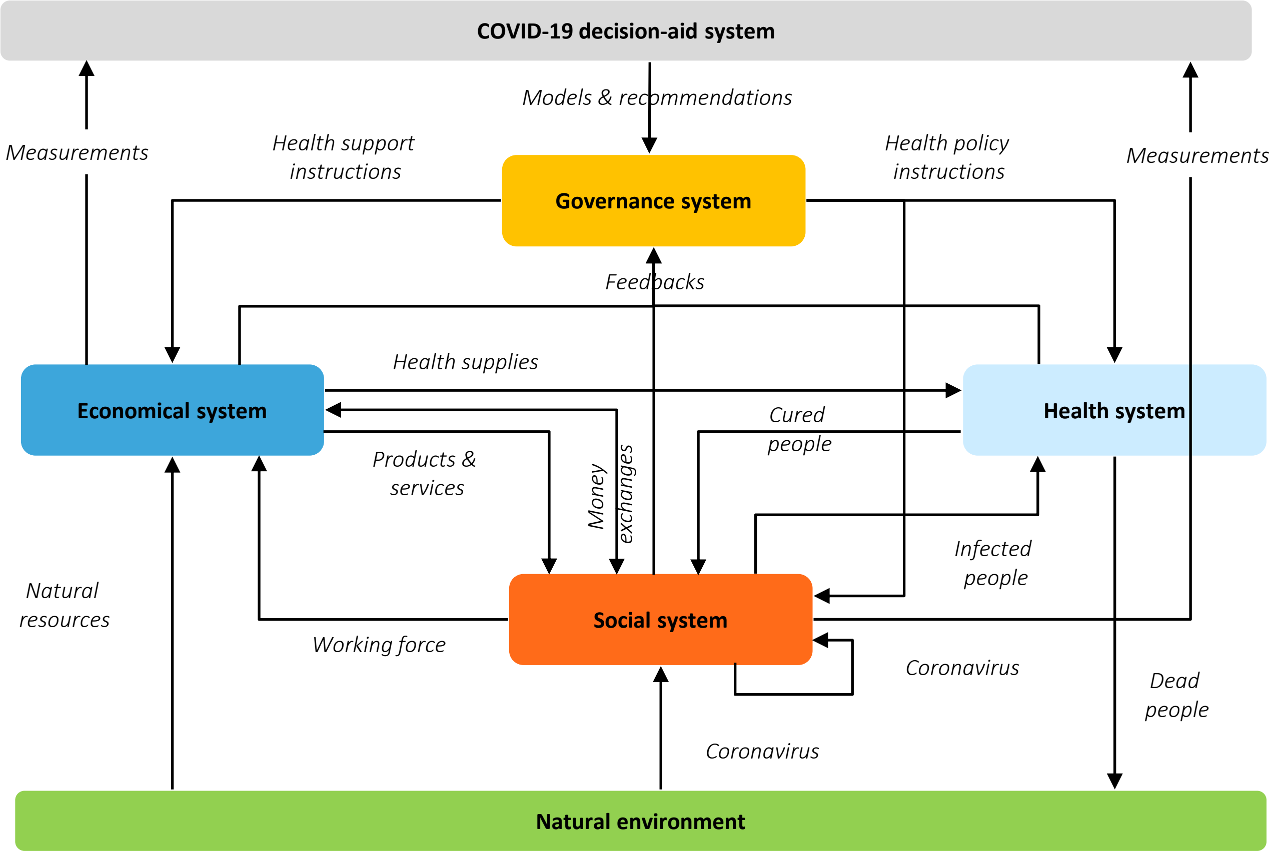
Systems Engineering best paper 2020



A **seminal paper** where we proposed a **systemic digital twin approach** for modeling the world in the covid-19 crisis context

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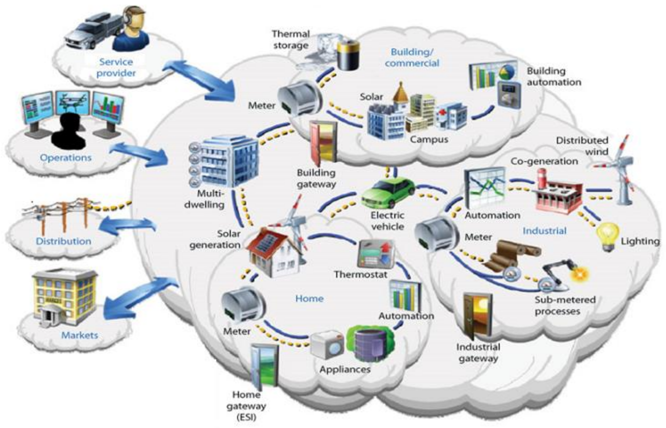
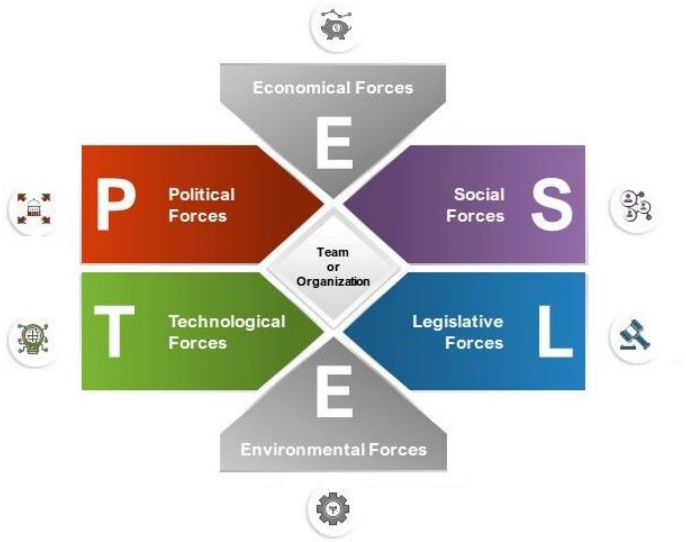
The context: industry has to manage more & more complexity (1/2)

Complex supply chains



Complex operations and maintenance

Complex industrial systems



Complex environment

Modern industries are permanently dealing with many **complex internal & external interdependent systems**. They shall of course manage **complex operational systems** such as their supply chain, their production systems, their distribution systems, their customer operations, their maintenance systems, etc., but they must also take into consideration **complex economical, political, social, technological, legal and environmental constraints** from a tactical and strategic perspective.

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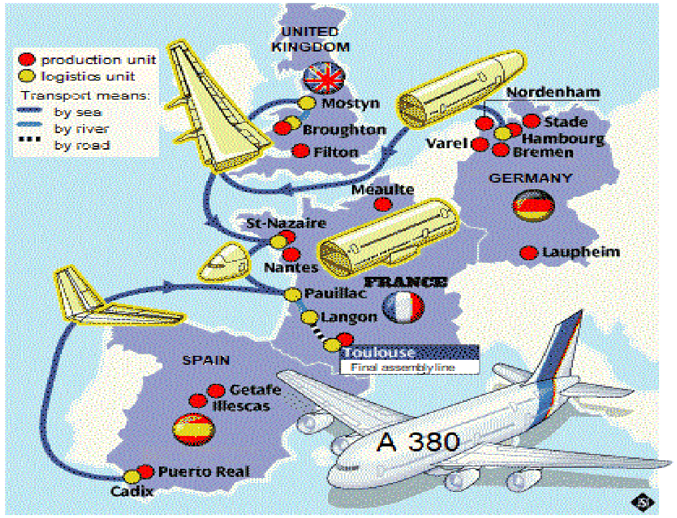
The context: industry has to manage more & more complexity (2/2)

Product



Industrial company

Economic sector

Global economy

Industrial optimization can moreover be approached at **several systemic scales**: that of the **product**, that of the **industrial company** that designs it, that of the associated **economic sector** and that of the **economy as a whole**, and each has its own difficulties. Managing and integrating smoothly these different scales appear to be a **key difficulty**.

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The issue: operations rely on operational, tactical & strategic decisions

- What is the optimal global architecture for an industrial system?
- What is the optimal design for a new industrial facility?
- 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 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**

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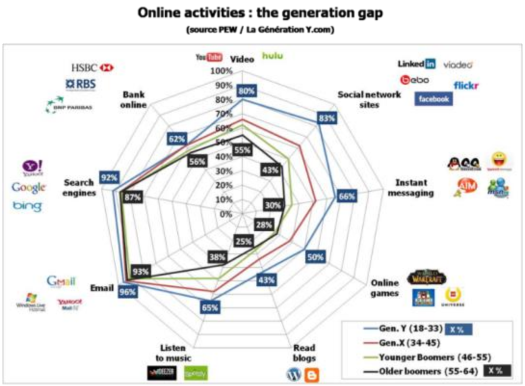
The challenge: how to be sure to take the right decisions?



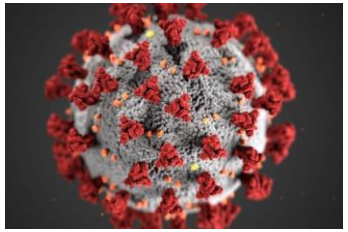
Change of consumption behaviors

Sustainable development goals

Economic uncertainty

Increase of regulations

Energetic transition challenge



Covid-19 crisis

In such complex environments, being able to **take the right operational & strategic industrial decisions** becomes key!

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Examples of industrial case studies (1/2)

Strategic planning of industrial systems

AIRBUS

A220 industrial system strategic planning

DunKerque PORT

Logistic hub strategic planning

Industrial optimization of industrial systems

fives

Automated warehouse design

NORDIC MINING

Submarine mining design

SNCF RÉSEAU

New railway signaling system design

Our **systemic digital twin case studies** are dealing with **strategic planning**, that is to say how to **manage optimally the evolution** of an industrial system, and with **industrial optimization**, that is to say how to **design / operate / maintain optimally** an industrial system.

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Examples of industrial case studies (2/2)

Case studies	Industrial system of interest	Nature of the flows
AIRBUS	A220 extended industrial system (manufacturing & supply chain)	Aircraft components
DunKerque PORT	Dunkirk port logistic hub	Containers & goods
fives	Automated logistic warehouse	Packs & goods
NORDIC MINING	Mining infrastructure	Minerals
SNCF RÉSEAU	Railway infrastructure	Trains

All these **industrial case studies** are dealing with **complex industrial systems** that can be seen as **discrete event systems** managing **various types of flows**.

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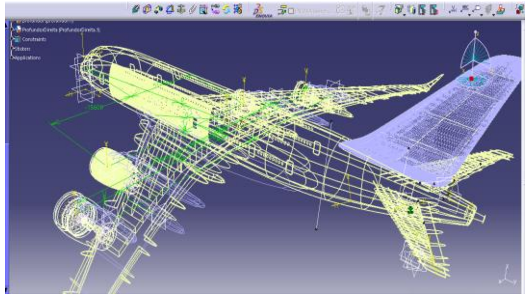
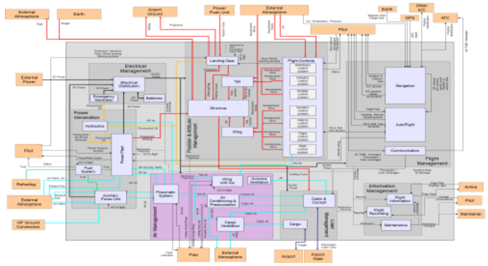
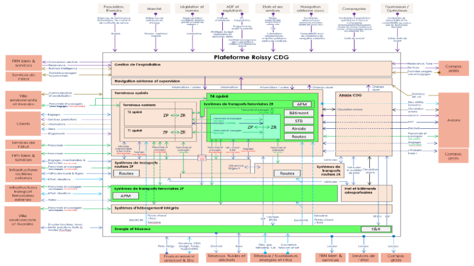
Systemic digital twin: a functional paradigm (1/2)

	Industrial products	Industrial processes
Geometrical (what can be seen from the system)	 *Example: geometric model of an aircraft*	 *Example: geometric model of an airport*
Functional (what is doing the system)	 *Example: functional model of an aircraft*	 *Example: business model of an airport*

Systemic digital twins

We shall focus here on **systemic digital twins** which simulate **industrial processes** of **complex industrial systems**

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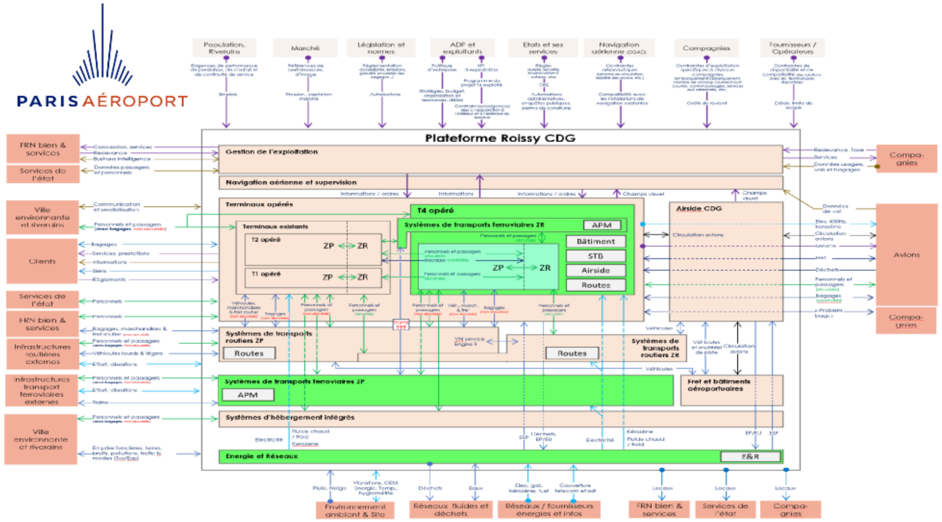
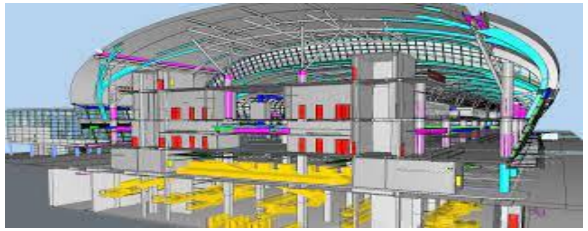
Systemic digital twin: a functional paradigm (2/2)

IOT & RFID infrastructure

Smart devices



Enterprise business processes



Digital mock-ups

Building Information Modeling (BIM)

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

We do believe that one must focus on **enterprise business processes**: a digital twin shall indeed be able to **model & simulate the behavior of an enterprise**, starting from operational data and ending by enriching decision dashboards or digital mock-ups, which put enterprise models at the core of a digital twin. This is why we took an **enterprise architecture behavioral approach** – based on formal modeling to support simulation by design – which is our key difference with respect to existing digital twin technology.

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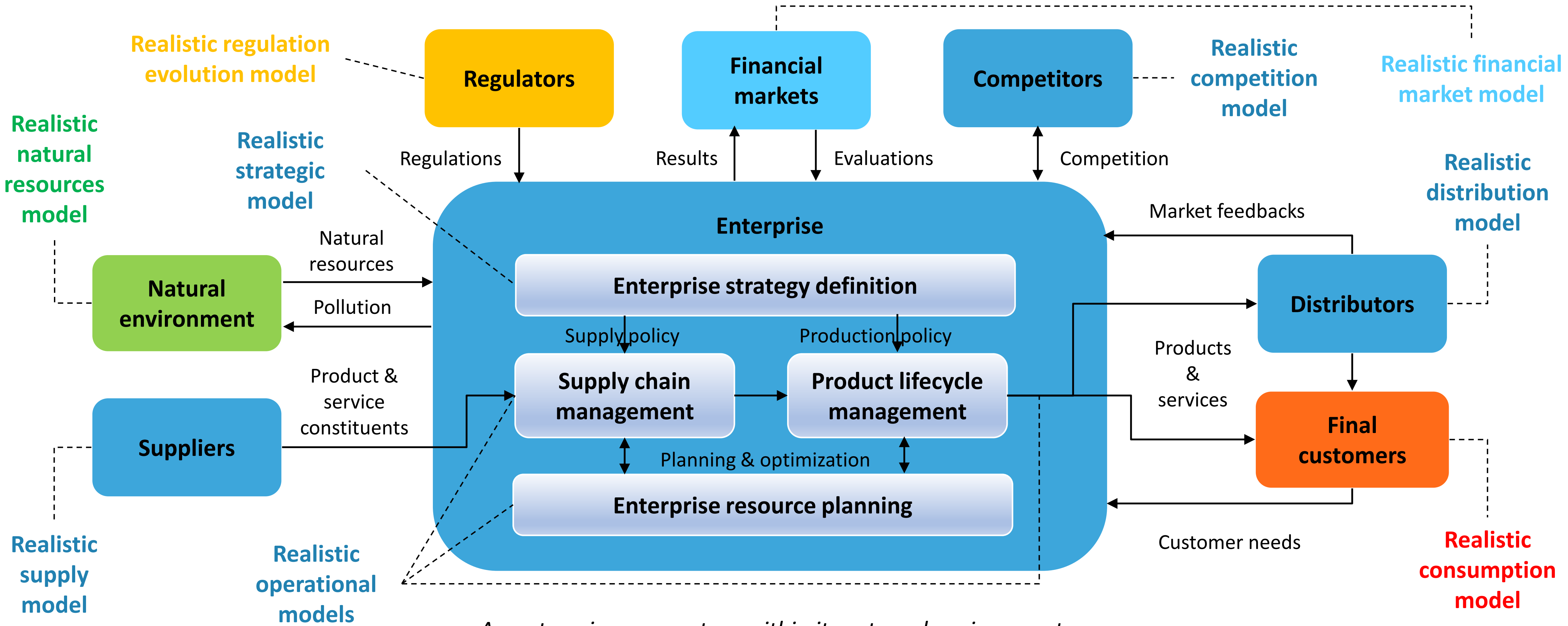
Our approach: a systemic vision to address enterprise complexity



An enterprise as a system within its external environment

To address enterprise complexity, our **approach** is based on an **unified enterprise systemic vision** that can support **operational & strategic analyses**. An enterprise shall here be considered in its whole within its external environment as an **unique integrated system** which shall be – as realistically as possible – modeled & simulated by **integrating coherently** many realistic specialized models.

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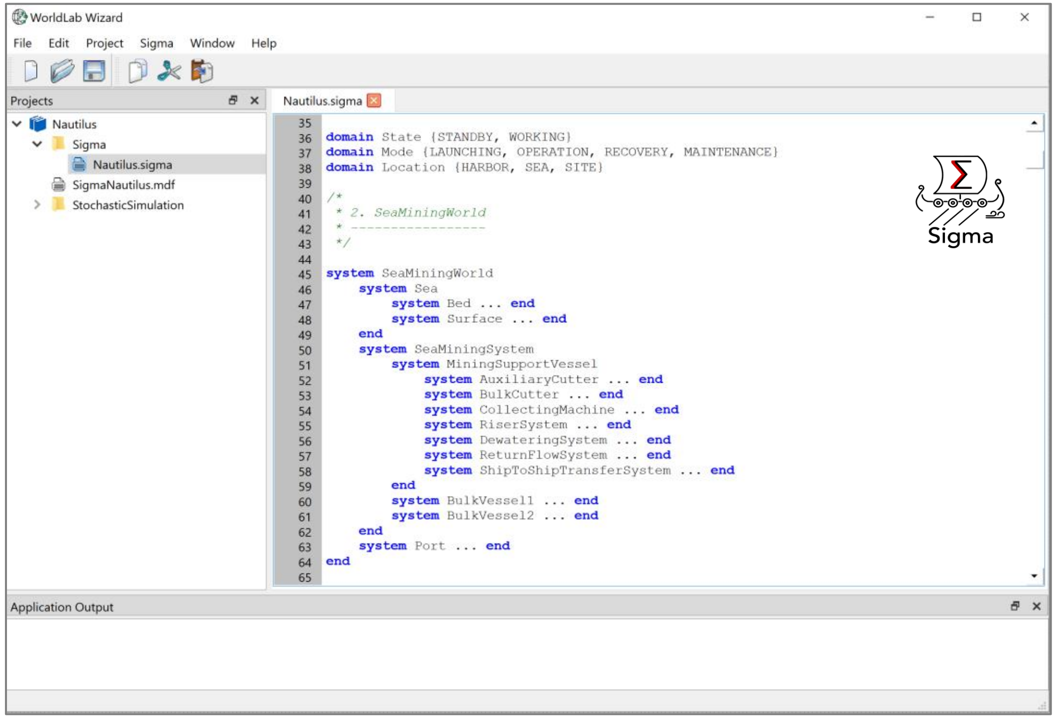
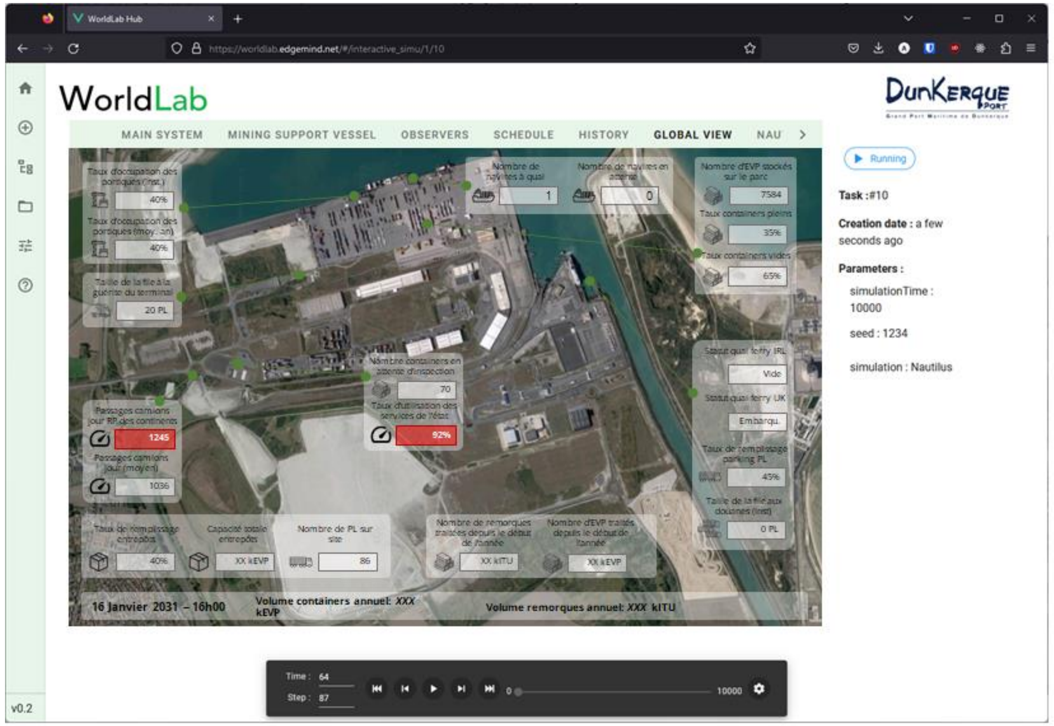
Our technology: the WorldLab systemic intelligence workshop (1/2)



WorldLab ™ Workshop



WorldLab ™ Hub

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 enterprise systemic modelling and scenario stochastic simulation & evaluation capabilities.

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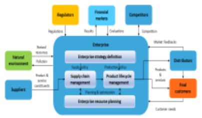
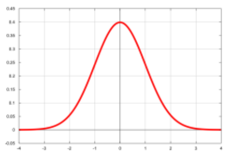
Our technology: the WorldLab systemic intelligence workshop (2/2)

- **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 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.

- **Data Abstraction – Operational data** are managed through **abstraction mechanisms** that allow to avoid dealing with details when they are not mandatory, while focusing on the most important trends captured by the data. This choice also allows to gain into execution performance when one needs to deal with complex simulations.

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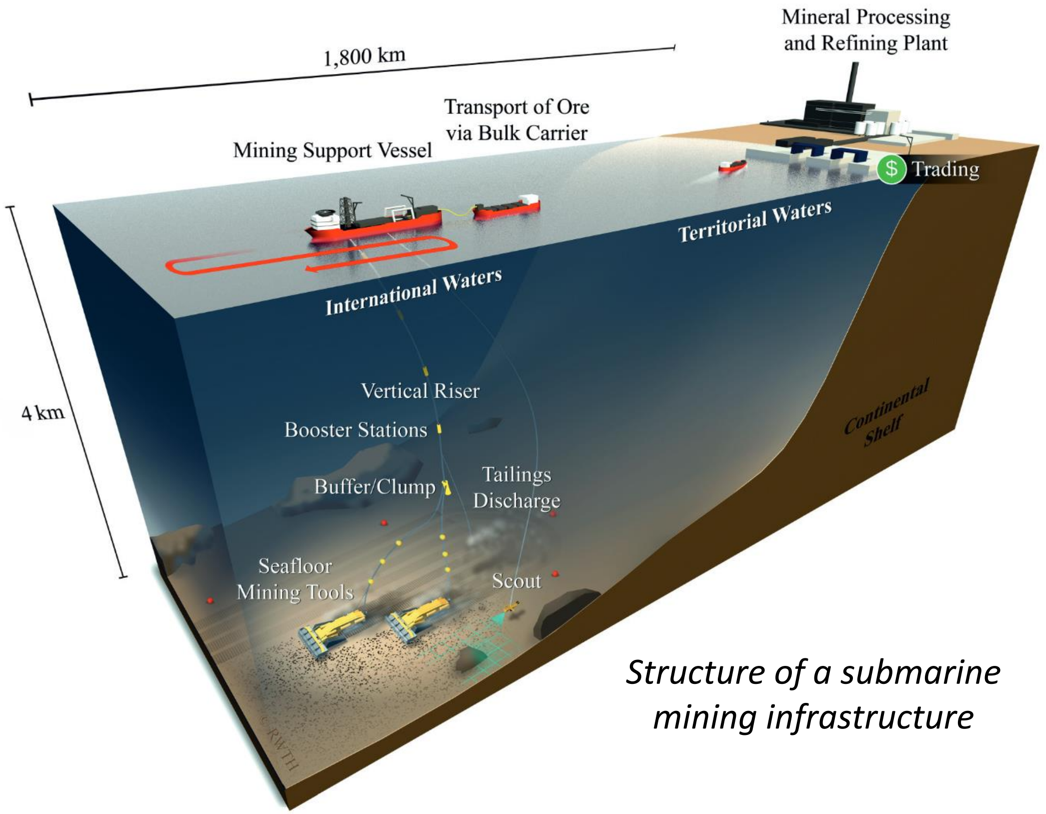
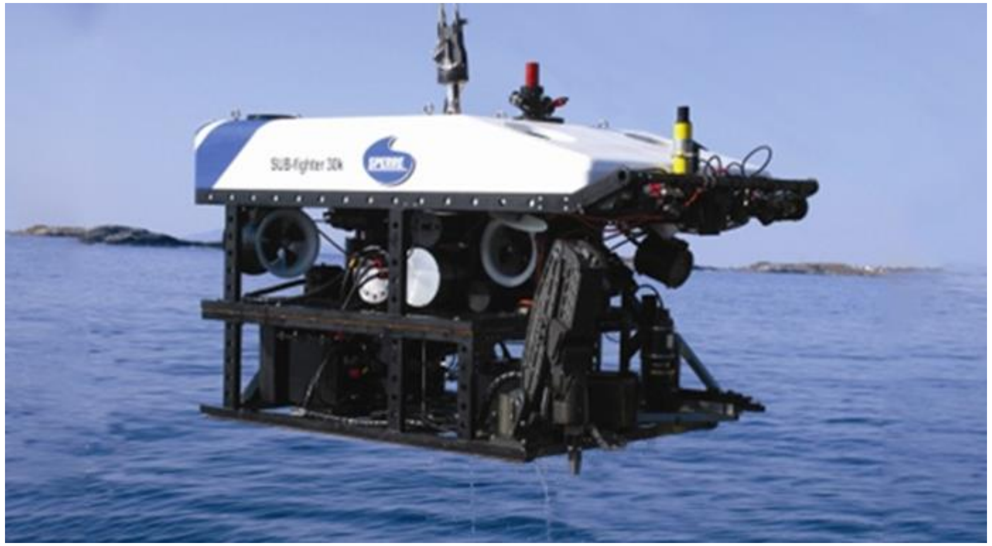
A case study of WorldLab™ technology: underwater mining

Motivation of the case study



Structure of a submarine mining infrastructure



Seabed robot dedicated to submarine ore collecting

Nordic Mining asked us to **identify the best design parameters to choose for a new underwater mine located in the middle of the North Sea** (around 2,000 km far away from the coast) in order to **minimize its energetic & environmental footprint**, which can be rephrased as an objective of minimizing its global energy consumption and its wastes during operations

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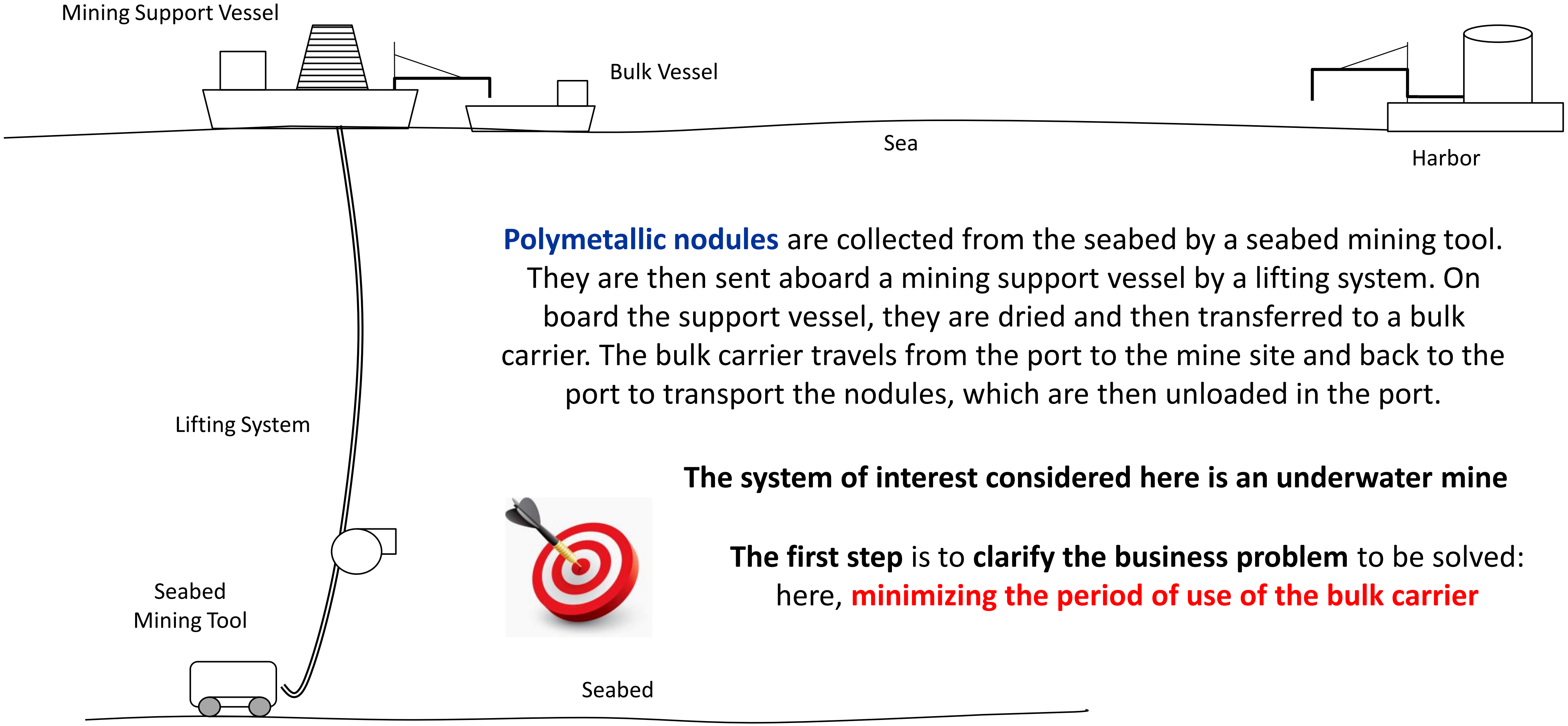
A case study of WorldLab™ technology: underwater mining
Overview of the case study



Polymetallic nodules are collected from the seabed by a seabed mining tool. They are then sent aboard a mining support vessel by a lifting system. On board the support vessel, they are dried and then transferred to a bulk carrier. The bulk carrier travels from the port to the mine site and back to the port to transport the nodules, which are then unloaded in the port.

The system of interest considered here is an underwater mine

The first step is to **clarify the business problem** to be solved: here, **minimizing the period of use of the bulk carrier**

An application case of WorldLab ™ technology: an underwater mine

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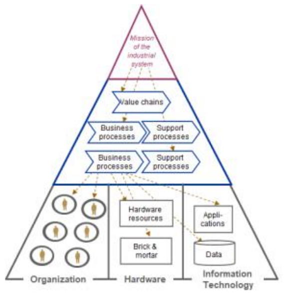
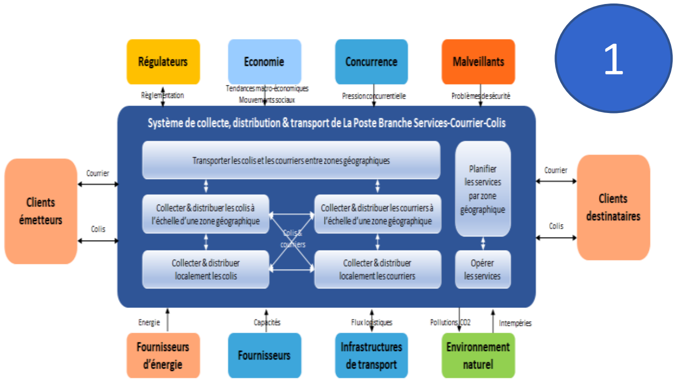
A case study of WorldLab™ technology: underwater mining

The three main steps for developing a systemic digital twin



Model-Based Systems Engineering (MBSE)



MBSE model of an industrial system

2

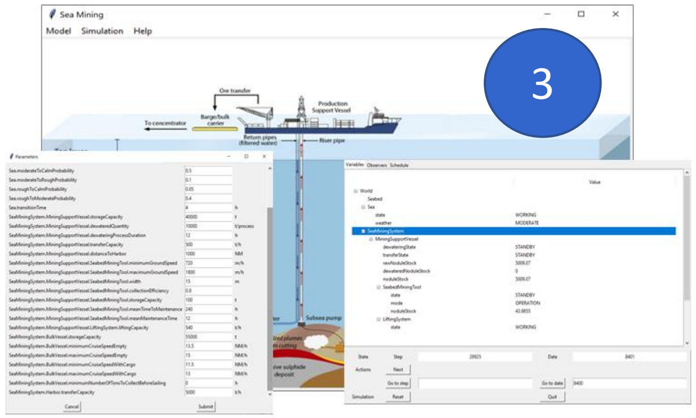
```
system World
  system Supplier ... end
  system Producer ... end
  system Consumer ... end
end

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
```

Σ^{TM} model of an industrial system



System digital twin of an industrial system

The methodological framework for the development of a systemic digital twin with Σ^{TM} and WorldLab ™

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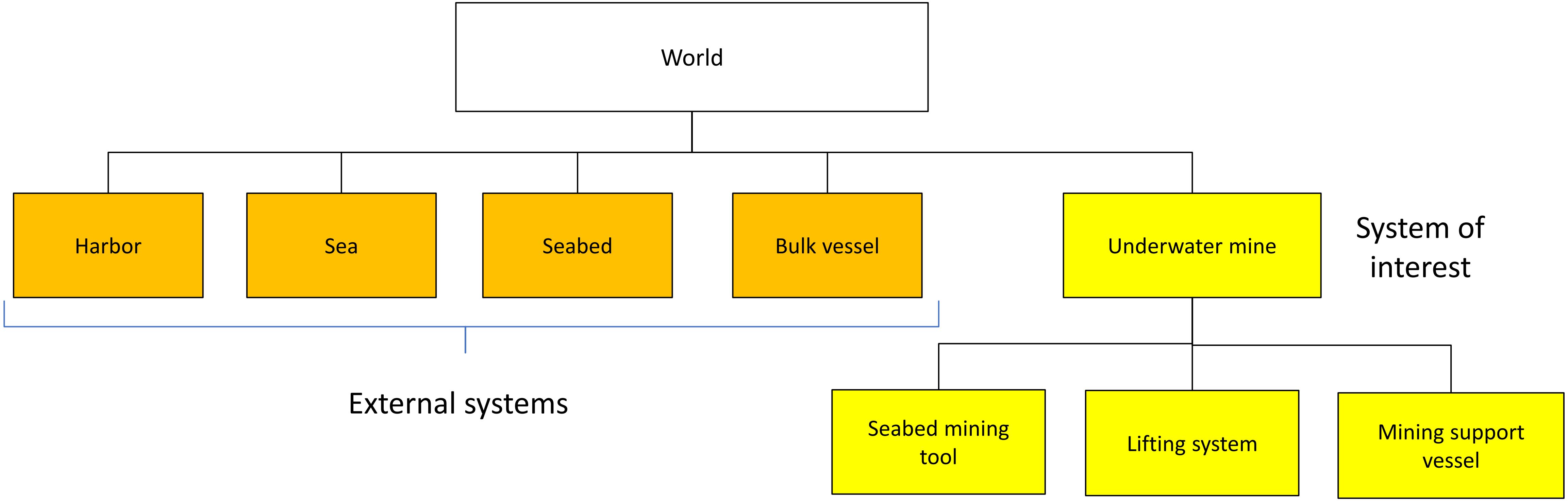
A case study of WorldLab™ technology: underwater mining
Step 1: design of the systemic digital twin (1/3)



System breakdown of the environment of the system of interest

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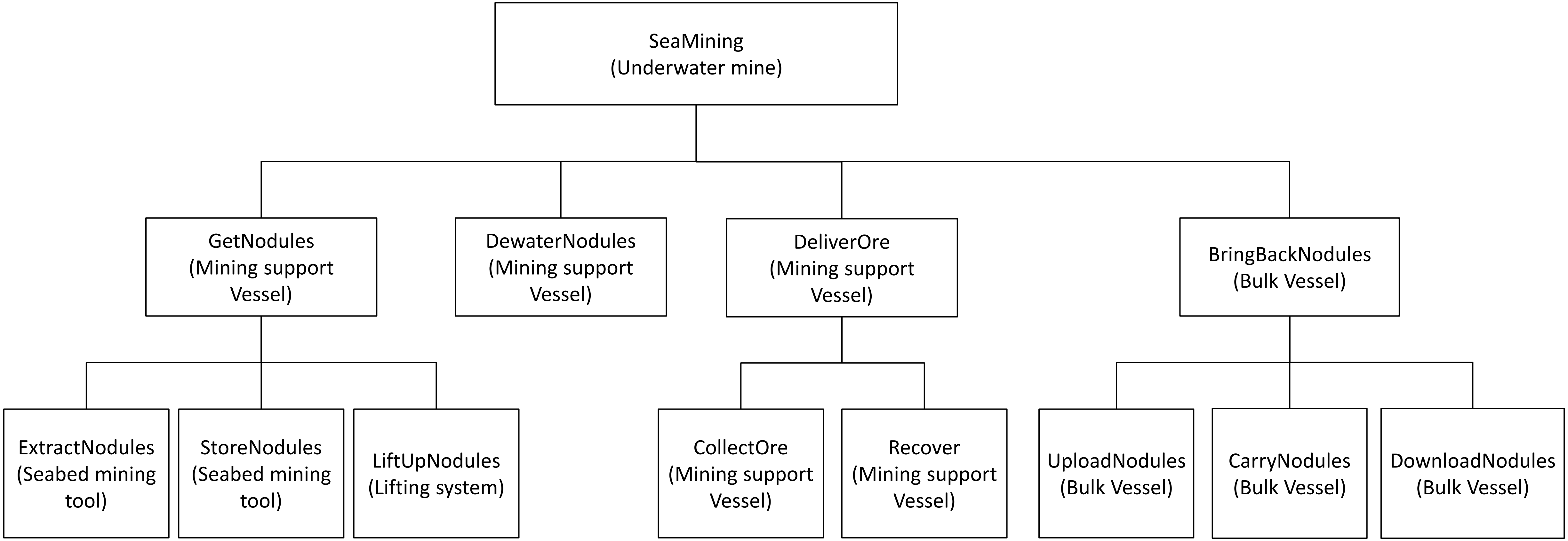
A case study of WorldLab™ technology: underwater mining

Step 1: design of the systemic digital twin (2/3)



Functional breakdown of the perimeter of interest (simplified)

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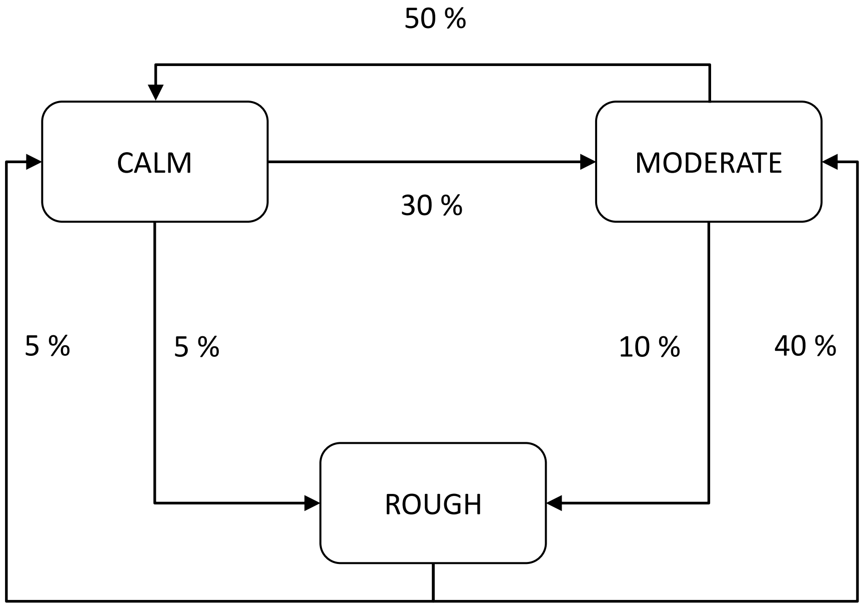
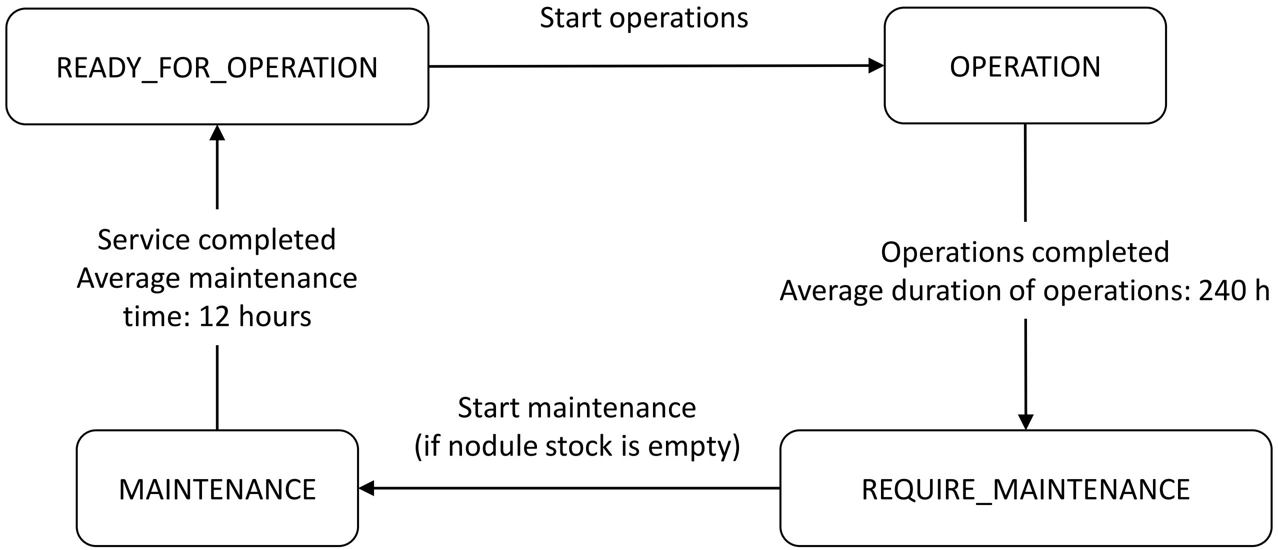
A case study of WorldLab™ technology: underwater mining
Step 1: design of the systemic digital twin (3/3)



Modeling of the state of the sea on site over a time step of 4 hours (based on historical data)



Modeling of the operations of the seabed mining tool

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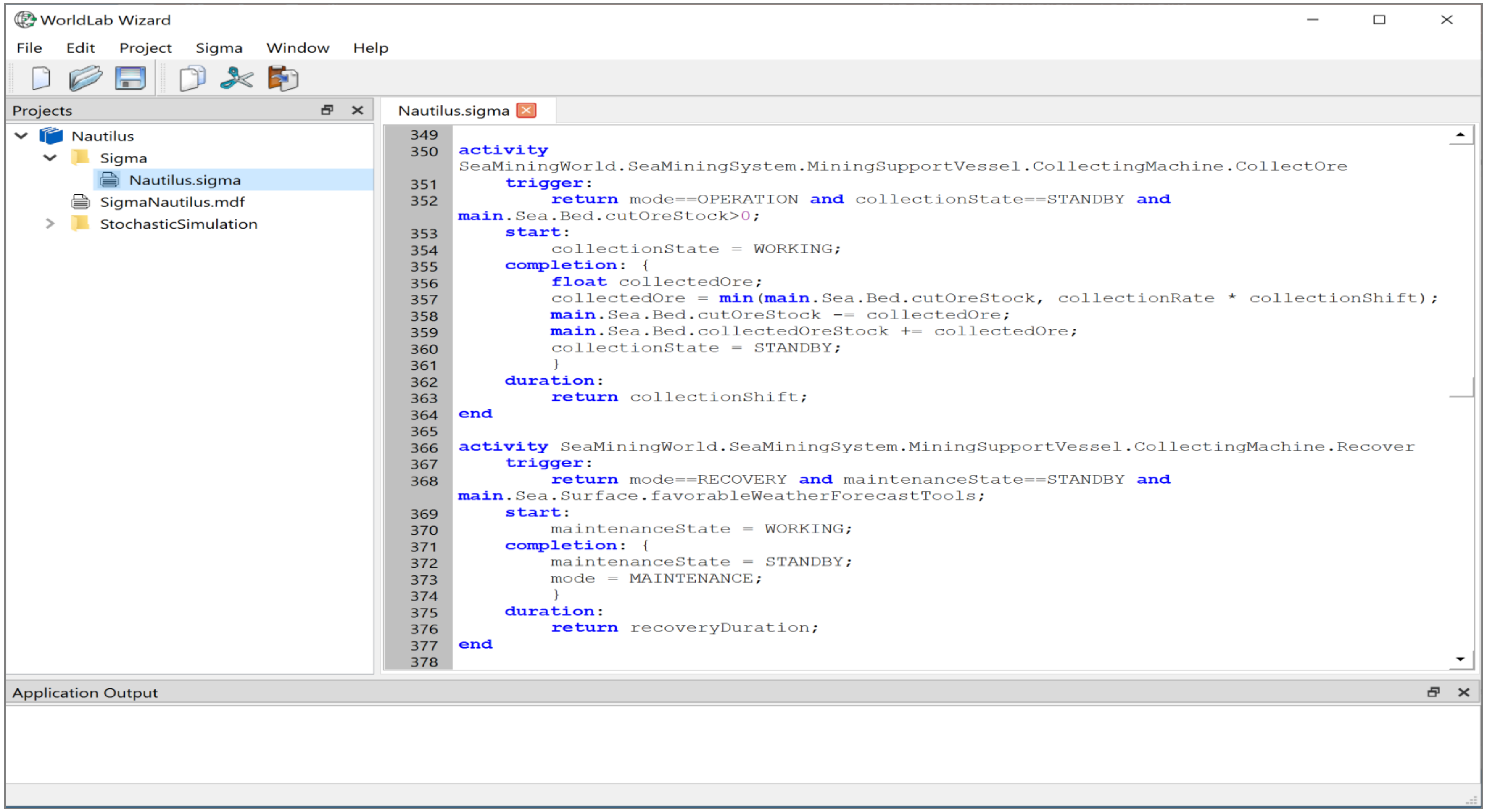
A case study of WorldLab™ technology: underwater mining

Step 2: development of the systemic digital twin



Specification in Σ™ of a sub-marine mining exploitation, supported by WorldLab ™ systemic intelligence workshop

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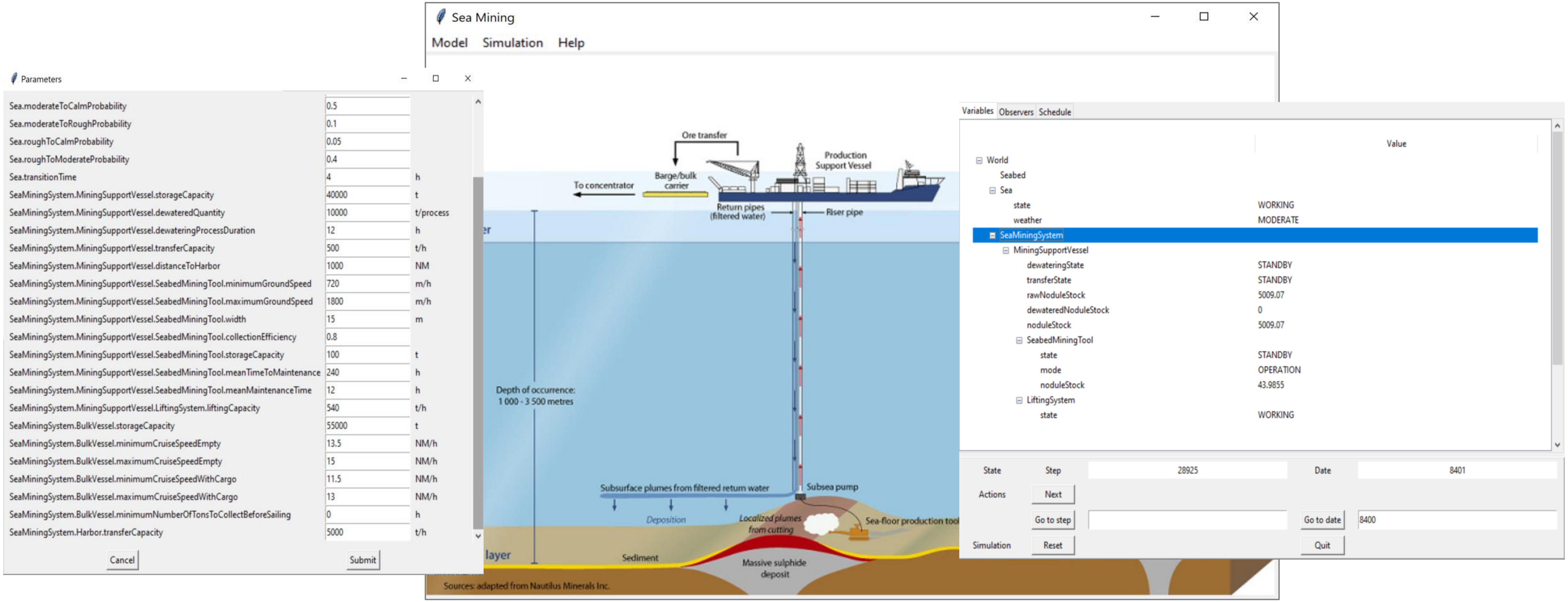
A case study of WorldLab™ technology: underwater mining
Step 3: use of the systemic digital twin



Example of a systemic digital twin for a sub-marine mining exploitation which was constructed with WorldLab™ systemic intelligence workshop

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Agenda

1. Systemic Intelligence Group
2. Modeling & simulation of industrial systems
3. Systemic digital twins of industrial systems
4. An illustrative example: a submarine mine
5. **Questions & answers**

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Thanks for your questions

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