Factory SoS Modelling and Simulation

State of the Art Analysis – version 1.0

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1. Management Summary

This document provides an overview on the state of the art for modelling and simulation of Factories of the Future (FoF). It is created as state of the art analysis in the work package *WP3 – FoF Modelling and Simulation* of the ITEA project CyberFactory#1[1] (in the following also CyberFactory or CF#1 for short).

CyberFactory#1 aims at designing, developing, integrating and demonstrating a set of key enabling capabilities to foster optimisation and resilience of the Factories of the Future. It will address the needs of pilots from transportation, automotive, electronics and machine manufacturing industries around use cases such as statistical process control, real time asset tracking, distributed manufacturing and collaborative robotics. It will also propose preventive and reactive capabilities to address security and safety concerns to FoF like blended cyber-physical threats, manufacturing data theft or adversarial machine learning.

Regarding modelling and simulation, the project focuses on four key enabling capabilities of the FoF:

- CPS modelling and digital twins
- Ecosystem modelling
- Human behavior modelling
- Factory SoS modelling

This document is structured along those key capabilities: Chapter 2 introduces basic concepts of digital twins (DT) and co-simulation for the combination of multiple simulations (Section 2.1), followed by an overview of existing frameworks for simulation and digital twins (Section 2.2). Chapter 3 provides an overview on (theoretical) modelling approaches and existing modelling tools for ecosystem modelling, including an introduction on modelling of cyber risks in supply chain security. Chapter 4 focuses on solutions for representing human behaviour in the FoF. This chapter is not only sketching on how the interaction of humans and machines is addressed recently, but also on how to access the influence on evolving factory environments to human welfare and needed capabilities of human workers. Chapter 5 presents on how the integration of previous aspects (CPS modelling, ecosystem modelling, human behaviour modelling) for modelling the FoF as system of systems (SoS) is done in the state of the art and available tool support. Each chapter concludes with a short discussion on limitations in the state of the art for covering the respective capability.

The primary results of the state of the art analysis include the following:

- The development of digital twins for mirroring and monitoring of factory subsystems is successfully done by academics and developers, commercial and non-commercial tool support exists. Nevertheless, the existing frameworks are limited in their scope: There is a lack of modelling methods and tools that reflect e.g. optimization, safety, security and resilience based on a holistic approach.

[1] https://www.cyberfactory-1.org

- Ecosystem modelling approaches can support the identification of key actors and their goals and relations in the (business) ecosystem, improving the understanding of e.g. value chains and operational dependencies. One of the main remaining challenges is how to gather information for instantiating a model for a specific ecosystem, especially if taking into account that some ecosystem actors are not eager to share economic details.
- The representation of human behaviour in digital twins is not yet covered in detail in the state of the art. One of the key challenges for integrating human worker aspects in DTs is the collection of data on humans: unlike machines, humans are not equipped with sensors that provide information for updating a digital representation of the FoF.
- Although digital twins exist for some applications, there do not exist standards for combining digital twins. Hence, optimization methods using digital twins are restricted to the optimization of individual components. There is a gap how the overall FoF can be optimized and resilience can be increase.

2. CPS Modelling and Simulation

This chapter gives an overview about the state of the art regarding modelling and simulation of CPS with application in factory environments. Therefore general concepts are introduced in Section 2.1. Then corresponding frameworks and standards are introduced in Section 2.2. Finally an overview about the presented frameworks and a discussion regarding the usability of concepts is done in Section 2.3.

2.1. Modelling and Simulation Concepts for CPS

This section focus on the two concepts *digital twin* and *co-simulation*. For each concept there is a general description as well as an example of use in the production environment.

2.1.1. Digital Twin (DT)

Description of concept

Cyber-Physical Systems (CPS) can be defined as the connection and interaction between the physical and a computational world[2] [3]. Sensors, actors, communication and information technology gathers constantly information from the physical domain. The information flow is led to a virtual system. One concept to realize the virtual part is the digital twin (DT). While Negri et al. already describe the DT as the “virtual counterpart of a physical system”[4], Lu X. et al. introduced the DT directly as a solution of the cyber part of a CPS exemplary for the production domain. The DT can extend the physical production world with its manufacturing assets, human employees, whole factories or production networks to a set of CPS with an own virtual cyber world[5].

The concept of DTs was initially developed for the aerospace domain and still becomes a relevant topic for other contexts especially factory and production. Researchers focus on the DT differently and no clear definition exists[6]. However there is a wide consent that a DT distinguishes from a CPS by emerging from a combination of metadata and real-time data which describe how the physical domain is used. The sum of these data can be recognized as a dynamical system which represents the current state of the physical domain and is called DT[7].

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[2] “CYBER-PHYSICAL SYSTEMS: Enabling a Smart and Connected world,” National Science Foundation, [Online]. Available: https://www.nsf.gov/news/special_reports/cyber-physical/ [Accessed 17 03 2020].
[3] A. A. Lee, “Cyber Physical Systems: Design Challenges,” Berkeley, 2008.
[4] E. Negri, L. Fumagalli and M. Macchi, *A review of the roles of Digital Twin in CPS-based production systems,* Modena, 2017.
[5] Y. Lu, C. Liu, H. Huang, K. I.-K. Wang and X. Xu, "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues," *Robotics and Computer-Integrated Manufacturing,* 02 2020.
[6] E. Negri, L. Fumagalli and M. Macchi, A review of the roles of Digital Twin in CPS-based production systems, Modena, 2017.
[7] S. Boschert and R. Rosen, “Digital Twin - The Simulation Aspect,” in Mechatronic Futures, München, Germany, Springer, 2016, pp. 59-74.

Moreover Malakuti et al. define the DT as "a formal digital representation of a real physical system that captures attributes and behaviours" and focus on data collection[8]. If different applications and functions collect their data independently by their own, information is distributed to several locations and probably available in multiple formats. To avoid these "scattered information", the DT can act as a central data collector providing information for different capabilities. Then, the DT can also be used as a foundation for advanced analytics and artificial intelligence applications.

Furthermore the authors say that the collectable data is available through the overall production process. Detailed product information by the manufacturer as well as environment or live data from the customer can be stored in the DT even if that data comes from different involved parties. Lu X. et al. also mention the lifecycle aspect and remark the necessity of a data model. Therefore they provide an overview about information models for different lifecycle phases[9].

Rosen et al. require, that those data should be accessible in a holistic way covering data from sensors, about the behaviour, the product and the production process. They define the DT as updated live representation of the full environment and process state available at runtime. Therefore it can anticipate the consequences of actions by behaviour simulation which extends an automated system to an autonomous one[10]. Of course this requires a frequent update of collected data.

These authors also reflect to the role of DTs in the FoF. They describe the FoF as a structure of more and more distributed and independent units, managing itself and interacting together[11]. Regarding the message that each physical asset has a DT representing in the cyber world, the DT should also capture these interactions. Such a capability is presented by Malakuti et al. by different types of relationships of DTs[12]. DTs can be composed hierarchically like a factory with its containing productions units or associational, if i.e. counterparts represent material producer and consumer in production lines. Also a peer-to-peer composition is mentioned if a network of DTs with similar functions or similar products as outputs exists.

DT example for a prodution environment

Rosen et al. gives an example how digital twins can be used for a production chain[13]. Suppose a factory with several production assets for a part workflow (Compare to Figure

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[8] S. Malakuti, P. van Schalkwyk, B. Boss, C. R. Sastry, V. Runkana, S.-W. Lin, S. Rix, G. Green, K. Beachle and S. V. Nath, "Digital Twins for Industrial Applications," 2020.
[9] Y. Lu, C. Liu, H. Huang, K. I.-K. Wang and X. Xu, "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues," Robotics and Computer-Integrated Manufacturing, 02 2020.
[10] S. Boschert and R. Rosen, "Digital Twin - The Simulation Aspect," in *Mechatronic Futures*, München, Germany, Springer, 2016, pp. 59-74.
[11] R. Rosen, G. von Wichert, G. Lo and K. D. Bettenahsuen, "About The Importance of Autonomy and Digital Twins for the Future of Manufacturing," *IFAC-PapersOnLine,* pp. 567-572, 2015.
[12] S. Malakuti, P. van Schalkwyk, B. Boss, C. R. Sastry, V. Runkana, S.-W. Lin, S. Rix, G. Green, K. Beachle and S. V. Nath, "Digital Twins for Industrial Applications," 2020.
[13] R. Rosen, G. von Wichert, G. Lo and K. D. Bettenahsuen, "About The Importance of Autonomy and Digital Twins for the Future of Manufacturing," IFAC-PapersOnLine, pp. 567-572, 2015.

8 in [14]). Every asset and produced part has its own digital twin which status is updated frequently. Information like part type, production order & priority, skill and tool list for each operation step, production history and the current states and locations for assets and parts are available.

Together with the simulation feature of the digital twins, those live data enables prediction of consequences for decision making. Suppose the next operation for a part is drilling, both the drilling and milling machine can execute this operation and both machines are free. Then the digital twin can simulate both opportunities to decide which one is the best with respect to given performance indicators.

2.1.2. Co-Simulation

For simulating a CPS different authors present co-simulation as a suitable approach, especially for simulating complex systems[15] [16]. Steinbrink defines co-simulation “as the coordinated execution of two or more models […] in their runtime environments”[17]. Two dimensions for comparison of simulations can be derived from that definition, which are also considered in Figure 1. On the one hand simulations can be distinguished by their number of models or modelling tools, on the other hand by the number of solvers or executing simulation engines. The following simulation types including co-simulation are described as follows:

Classic Simulation

The execution of one model with one simulation engine is called a “Classic Simulation”. Considering the role of CPS in the FoF that a CPS is rather one of several components like a machine in the plant, that complete monolithic simulation type might not be suitable.

Hybrid/Merged Simulation

Because each CPS could come up with its own distinguishing model, at least a “Hybrid/Merged Simulation” is required for an overall simulation. This type allows the combined execution or coupling of more than one model by a single solver. Embedding the CPS in the FoF context the CPS is also connected to other models e.g. for peoples, factories or networks of them[18]. Therefore the combination of models is also important for a domain agnostic simulation type. Different models are also required by the DT because of the different aspects to simulate. For instance there are models for CAD, electricity, functional sequences, logistics and more.

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[14] R. Rosen, G. von Wichert, G. Lo and K. D. Bettenahsuen, “About The Importance of Autonomy and Digital Twins for the Future of Manufacturing,” IFAC-PapersOnLine, pp. 567-572, 2015.
[15] B. Wang and J. S. Baras, *HybridSim: A Modeling and Co-simulationToolchain for Cyber-Physical Systems,* Maryland, 2013.
[16] C. Gomes, C. Thule, D. Broman, P. G. Larsen and H. Vangheluwe, “Co-simulation: State of the art,” 2017.
[17] C. Steinbrink, *A Non-Intrusive Uncertainty Quantification System for Modular Smart Grid Co-Simulation,* Oldenburg, 2017.
[18] Y. Lu, C. Liu, H. Huang, K. I.-K. Wang and X. Xu, "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues," Robotics and Computer-Integrated Manufacturing, 02 2020.

Parallel Simulation

“Parallel Simulation” extends the “Classic” simulation with additional solvers for example to reduce computation time[19]. Therefor it can be useful for very complex problems with large scale grids which is expectable in fabric simulations. Nevertheless there is still one model for the overall system, but the execution is distributed to more than one simulation engine.

Co-simulation

With co-simulation different models can be executed by their own individual simulation engines. This flexible setup allows an individual exchange of whole simulation entities. Therefore also complete simulators can run together even if they are developed independently for several domains[20].

Steinbrink notes, that co-simulation also covers the interaction of Hard- and Software components. He points out, that hardware/software co-simulation includes “Hardware in the Loop” test approaches as well as the general realization of components in Hardware or Software[21]. According Pederson et al. also Human Machine Interfaces can be integrated to co-simulation setups for simulating Hard-/Software together with human behaviour (“Human in the Loop”)[22].

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[19] F. Schloegl, S. Rohjans, S. Lehnhoff, J. Velasquez, C. Steinbrink and P. Palensky, *Towards a Classification Scheme for Co-Simulation Approaches in Energy Systems,* 2015.
[20] C. Gomes, C. Thule, D. Broman, P. G. Larsen and H. Vangheluwe, “Co-simulation: State of the art,” 2017.
[21] C. Steinbrink, A Non-Intrusive Uncertainty Quantification System for Modular Smart Grid Co-Simulation, Oldenburg, 2017.
[22] N. Pedersen, T. Bojsen and J. Madsen, “Co-Simulation of Cyber Physical Systems with HMI for Human In The Loop Investigations,” Virginia Beach, 2017.

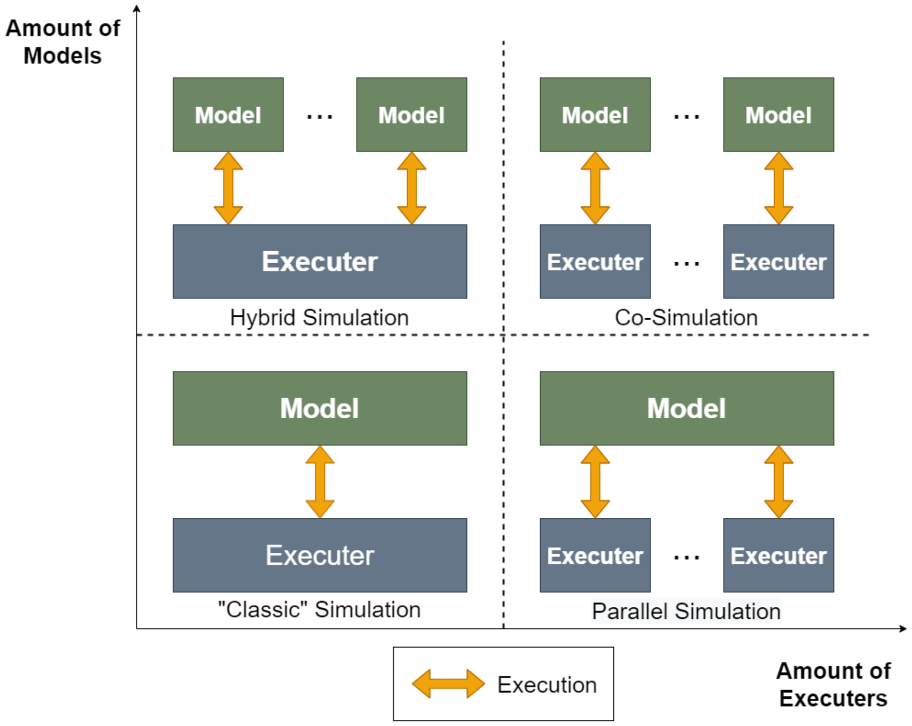

Figure 1: Distinction between co-simulation and other simulation types (adapted from [23]).

Orchestrating Co-simulation units

The usage of multiple – probable independently developed – simulation units requires an orchestration especially for controlling different timing behaviour[24]. According to Gomes et al. simulated units can behave according discrete event (DE) or continuous time (CT)[25]. Coupling these units leads to different orchestration methods. DE units change their values only at discrete time points triggered by events. Therefore the orchestration can be done by event handling. CT units can be orchestrated by value exchange in constant time frames, which may induce loss accuracy depending on the particular simulation models. The authors also consider a hybrid approach to couple DE and CT units together. Therefore one type is converted to the other by wrapping units:

- Hybrid DE – wrap every CT unit as a DE simulation unit, and use a DE based [25]
- Hybrid CT – wrap every DE unit to become a CT unit and use a CT based orchestrator[25]

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[23] C. Steinbrink, A Non-Intrusive Uncertainty Quantification System for Modular Smart Grid Co-Simulation, Oldenburg, 2017.
[24] A. Suzuki, K. Masutomi, I. Ono, H. Ishii and T. Onoda, CPS-Sim: Co-Simulation for Cyber-Physical Systems with Accurate Time Synchronization, 2018.
[25] C. Gomes, C. Thule, D. Broman, P. G. Larsen and H. Vangheluwe, “Co-simulation: State of the art,” 2017.

Distrete event unit example for a production system

Considering a production system e.g. in the FoF discrete event units can be suitable for simulating the reactive input output behaviour of a machine. Such an example is given by März et al. and described as follows[26]:

Imagine a machine with a buffer for incoming resources. If the buffer is empty the machine immediately consumes one resource and starts to work. After completion, the machine proceeds with the next resource from the buffer until the buffer is empty. This behaviour can be modelled with the arrival event of a new resource and the finish event of a machine.

Imagine a machine with a buffer for incoming resources. If the buffer is empty, the machine immediately consumes one resource and starts to work. After completion, the machine proceeds with the next resource from the buffer until the buffer is empty. This behaviour can be modelled with the arrival event of a new resource and the finish event of a machine. If the number of resources that are machined or waiting is described by a variable X, the arrival of a new event increases X. The finish event decreases X and starts a new manufacturing process if $X > 0$.

2.2. Frameworks for CPS Modelling and Simulation

A framework is a platform to develop software applications[27]. This includes predefined classes and functions. In the context of the FoF, frameworks that allow a scalable co-simulation between digital twins are most interesting. The DT of a FoF includes more than one component. In this chapter standards regarding simulation frameworks are introduced, following tools and current research which handle co-simulation.

2.2.1. Overview of Existing Standards

Gomes et al. introduced 87 frameworks for co-simulation[28]. We have filtered the presented corpus according to the following criteria:

- Out-of-date (Does not refer to a specific date, means newer publications are available)
- Missing relevance and applicability for FoF

Furthermore we conducted further research and added more frameworks. Within the research about frameworks several technics and standards have been detected especially for solving problems during the coupling of simulators. The most relevant standards are explained first in this section.

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[26] L. März, W. Krug, O. Rose and G. Weigert, Simulation und Optimierung in Produktion und Logistik, Heidelberg: Springer-Verlag, 2011.
[27] P. Christensson, «TechTerms - The Computer Dictionary,» [Online]. Available: https://techterms.com/definition/framework. [Zugriff am 08 04 2020].
[28] C. Gomes, C. Thule, D. Broman, P. G. Larsen und H. Vangheluwe, «Co-simulation: State of the art,» 2017.

Functional Mock-Up-Interface:

There is a great variety of modelling and simulation tools for different purposes. The **F**unctional **D**igital **M**ock-**U**p (FDMU) is a concept to combine traditional **Di**gital **M**ock-up **I**nterface (DMI) with behavioural simulation. To enable a collaboration in terms of a CT co-simulation, they can be connected through standardized interfaces as the **F**unctional **M**ock-up **I**nterface (FMI) delivers[29] [30]. The FMI has become a standard through a continuous rise of companies which integrate it in their tools. More than 100 tools support it including many notable companies e. g. Ansys, Dassault Systèmes and MathWorks[31]. The development is organized by the Modelica Association.

As stated the co-simulation uses different models and/or solvers. The FMI can be utilized to achieve an overall simulation with models from different supported tools. When a model is implemented by the FMI it is called **F**unctional **M**ock-up **U**nit (FMU)[32]. A FMU is an archive-file consisting of XML-files (definition of all variables of the FMU), C-code (functions to execute model equations) and further data (e. g. model icon)[33]. Through the standard interface the FMU blocks can be integrated into larger models.

The tool independency of the FMI leads mainly to two different use cases, the **M**odel **E**xchange (ME) and the **co**-**s**imulation (CS) of dynamic models[34]. The CS part can be basic, hybrid or scheduled. For the differences regard the following table[35].

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[29] E. Negri, L. Fumagalli und M. Macchi, *A review of the roles of Digital Twin in CPS-based production systems,* Modena, 2017.
[30] T. Blochwitz, M. Otter, J. Akesson, M. Arnold, C. Clauß, H. Elmqvist, M. Friedrich, A. Junghanns, J. Mauss, D. Neumerkel, H. Olsson und A. Viel, «Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models,» Lund, 2012.
[31] «fmi Functional Mock-Up Interface,» Modelica Association c/o PELAB, IDA, [Online]. Available: https://fmi-standard.org/tools/. [Zugriff am 06 04 2020].
[32] T. Blochwitz, M. Otter, J. Akesson, M. Arnold, C. Clauß, H. Elmqvist, M. Friedrich, A. Junghanns, J. Mauss, D. Neumerkel, H. Olsson und A. Viel, «Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models,» Lund, 2012.
[33] «Functional Mock-up Interface for Model Exchange and Co-Simulation,» Modelica Association c/o PELAB, IDA, [Online]. Available: https://fmi-standard.org/docs/3.0-dev/#_overview. [Zugriff am 06 04 2020].
[34] L. I. Hatledal, Z. Houxiang, A. Styve und H. Geir, «FMU-proxy: A Framework for Distributed Access to Functional Mock-up Units,» Regensburg, 2019.
[35] «Functional Mock-up Interface for Model Exchange and Co-Simulation,» Modelica Association c/o PELAB, IDA, [Online]. Available: https://fmi-standard.org/docs/3.0-dev/#_overview. [Zugriff am 06 04 2020].

Feature	Model Exchange	Basic Co-Simulation	Hybrid Co-Simulation	Scheduled Co-Simulation
Solver Included	✖	✔	✔	✔
Event Indicators	✔	✖	✖	✖
Early Return	✖	✔	✔	✖
Intermediate Value Access	✖	✖	✔	✔
Clocks	✔	✖	✖	✖
Direct Feedthrough	✔	✖	✖	✖

Table 1: Overview of the usability of FMI.

ME and CS differ in the way that ME uses an external solver and CS uses an internal solver. A master code which orchestrates the data exchange between the FMUs is not part of the FMI standard[36]. In most researches regarding FMI the authors came to the conclusion that every master code needs information of every simulation participant before the computation. So there is no plug-and-simulate process available[37].

Modelica

Modelica is an object-oriented modelling language for physical models e. g. mechanical, electrical, electronic, hydraulic, thermal, control or process-oriented subcomponents.[38] It offers an open standard that allows the simple and yet correct description of complex physical systems of all engineering disciplines by means of mathematical equations.

High Level Architecture for Modeling and Simulation

Whereas the FMI is used as standard for CT co-simulation the **H**igh **L**evel **A**rchitecture (HLA) is used as standard for DE co-simulation[39]. It was invented by the U.S. **D**epartment **of D**efense (DoD) during researches of distributed and parallel simulation[40]. The main goal was to find a possibility to link military training simulators. Due to its open architecture, it is now used in civil applications where the emphasis is on interoperability and reusability, including time management interoperability. HLA was standardized by the IEEE1516 in 2000.

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[36] «Functional Mock-up Interface for Model Exchange and Co-Simulation,» Modelica Association c/o PELAB, IDA, [Online]. Available: https://fmi-standard.org/docs/3.0-dev/#_overview. [Zugriff am 06 04 2020].
[37] T. Jung, N. Jazdi und M. Weyrich, «Dynamische Co-Simulation von Automatisierungssystemen und ihren Komponenten im Internet der Dinge,» Stuttgart, 2018.
[38] https://www.modelica.org/modelicalanguage
[39] C. Gomes, C. Thule, D. Broman, P. G. Larsen und H. Vangheluwe, «Co-simulation: State of the art,» 2017.
[40] S. Straßburger, «Overview about the High Level Architecture for Modelling and Simulation and Recent Developments,» Magdeburg, Germany, 2006.

Within HLA individual simulations are called federates. Different federates can build a federation and co-operate together. A **R**un-**T**ime **I**nfrastructure (RTI) enables a communication between all federates on a bi-directional basis[41]. Furthermore the RTI acts as simulation master and synchronizes participating federates. The entrance of new federates during run-time is possible, however depending on a federation agreement which has to be defined[42].

OPC Unified Architecture – OPC UA

OPC UA is a **S**ervice **O**rientated **A**rchitecture (SOA) for machine-to-machine communication. It is standardized in IEC 62541 and provides a semantic information model. Key characteristics are object orientation, scalability and a direct access to process data and metadata[43]. As of now OPC UA supports a wide range of various systems of different extend, performance or functional capabilities.

OSGi Alliance

A co-simulation can be realized on an OSGi framework basis. In this system components can be combined dynamically and reused at run-time. The OSGi framework is programmed in java and requires a java environment. In co-simulations technical components are represented in bundles leading to a distributable simulation[44]. In OSGi bundles are software components like a java class, HTML-data etc.

The OSGi-Framework delivers its functionality in different layers[45]:

- Security Layer (optional - for a digital signature of the code)
- Module Layer (Creates an environment for the importing and executing the bundles)
- Life Cycle Layer (Controls the life cycle of a bundle)
- Service Layer (For collaboration of the components

Multi-Agent System (MAS)

In general, MAS provide the possibility to model components and their interactions in different domains. It is not yet a standard, however has to be recognized due to its highly integrative nature and growing consideration in publications regarding co-simulation.

The purpose is to realize a dynamical co-simulation. In MAS each computing entity is referred to as an agent[46]. One feature is that the behavior of the agents is implemented through program logic. The agents can thus be implemented with different complexities and react intelligently to the environment. By building a network with other agents they can

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[41] S. Straßburger, «Overview about the High Level Architecture for Modelling and Simulation and Recent Developments,» Magdeburg, Germany, 2006.
[42] T. Jung, N. Jazdi und M. Weyrich, «Dynamische Co-Simulation von Automatisierungssystemen und ihren Komponenten im Internet der Dinge,» Stuttgart, 2018.
[43] S. Hensel, M. Graube und L. Urbas, «Co-Simulation with OPC UA,» IEEE, Dresden, 2016.
[44] OSGi Alliance, «The OSGi Alliance - OSGi Core,» 2018. [Online]. Available: https://osgi.org/download/r7/osgi.core-7.0.0.pdf. [Zugriff am 08 04 2020].
[45] B. Weber, P. Baumgartner and O. Braun, OSGi für Praktiker, München: Hanser, 2010.
[46] B. P. Gokulan und D. Srinivasan, «An introduction to Multi-Agent Systems,» Singapure, 2010.

learn to detect anomalies in the simulated environment. In terms of simulations an agent represents an IoT component as a so called agent-wrapper. The wrapping includes the complete simulation system where the computing runs within the agent. This enables a co-simulation with different tools.

By modelling, simulating and representing the IoT components in individual agents, these agents can enter and exit at runtime like real IoT components (plug and simulate)[47].

By being wrapped into an agent all components have standardized interfaces, similar to FMU. An agent system offers a platform where information can be exchanged. Additionally, it synchronizes the individual simulations and creates an environment to represent the physical interactions between the individual components. This concept is scalable.

In context of MAS the multi-agent programming language NetLogo is worth mentioning, it supplies an integrated modeling environment.

Discrete Event System Specification (DEVS)

DEVS is a set of conventions to specify discrete event simulation models for cyber physical systems. It was first introduced in 1976[48]. It can be used to support the modular model design. Some frameworks like the MECSYCO or the POWERDEVS uses the formalism. The DEVS expound the problem of discrete time simulation where the time steps t are discrete variables. Every transition step must be a multiple of t which limits the duration between inputs and outputs. Discrete event simulation of the other hand are continuous meaning that any pair of events can have varying time steps.

Within DEVS each simulation model is described as a DEVS atomic model which has input and output ports.

SystemC

SystemC is a generic standard and extends the programming language C++ with classes to provide an effective-driven simulation kernel[49]. It provides specific models for a variety of system components and means for easy configuration. SystemC is defined in IEEE 1666-2011.

MTConnect

Manufacturing Technology Connect, or MTConnect, is a communication protocol for data exchange between manufacturing resources in the shop-floor and software applications.[50]

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[47] T. Jung, N. Jazdi und M. Weyrich, «Dynamische Co-Simulation von Automatisierungssystemen und ihren Komponenten im Internet der Dinge,» Stuttgart, 2018.

[48] G. A. Wainer, R. Goldstein and A. Khan, "INTRODUCTION TO THE DISCRETE EVENT SYSTEM SPECIFICATION FORMALISM AND ITS APPLICATION FOR MODELING AND SIMULATING CYBER-PHYSICAL SYSTEMS," Ottawa, 2018.

[49] C. Menard, J. Castrillon, M. Jung and N. Wehn, "System Simulation with gem5 and SystemC," Pythagorion, Greece , 2017.

[50] L. Hu, N.-T. Nguyen, W. Tao, M. C. Leu, X. F. Liu, R. Shahriar and N. A. Sunny, "Modeling of Cloud-Based Digital Twins for Smart Manufacturingwith MTConnect," Elsevier B. V., Texas, USA, 2018.

By delivering a semantic vocabulary for manufacturing equipment to provide structured and contextualized data it standardizes factory device data.[51] In the working principle of MTConnect is shown.

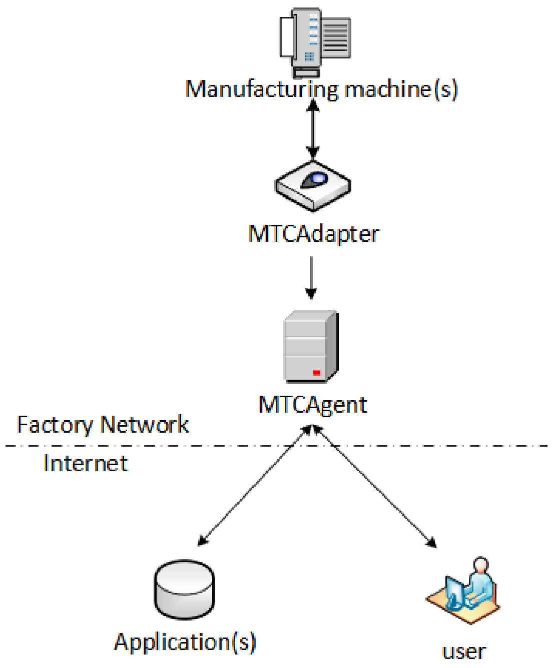


Figure 2: The working principle of MTConnect protocoll[52].

A MTCAgent aggregates information through a MTCAdapter of machines from the shop-floor. The information are provided to the users or applications in standard XML format.

2.2.2. Distinguishing Features for Modelling and Simulation Frameworks

The following table provides an overview on existing frameworks for CPS modelling and simulation in the context of the Factory of the Future (FoF), that are presented in this chapter. The following information is given for all frameworks:

- **Developers**: Name of the community or company who developed the framework
- **Active development**: Information on the development status of the framework. If the cell is checked with "X", this means that the development and maintenance of the framework is ongoing. Indicators for an active development status is the date of the release date of the latest version or the commit history (e.g. for open source frameworks).
- **Licence needed**: "X" indicates the need for a licence before using the framework.
- **Open source**: Crossed, if the source code of the framework is publicly available, not crossed, if great marts of the source code are not accessible by the user.

[51] https://www.mtconnect.org/

[52] L. Hu, N.-T. Nguyen, W. Tao, M. C. Leu, X. F. Liu, R. Shahriar and N. A. Sunny, "Modeling of Cloud-Based Digital Twins for Smart Manufacturingwith MTConnect," Elsevier B. V., Texas, USA, 2018.

- **Monolithic**: Indicates if the framework is a closed system or if it is applicable for co-simulation. “X” indicates a monolithic framework, otherwise there is possibility to add other simulations for co-simulation.
- **Distributable**: (Only assess if framework is “non-monolithic”) “X” if it is possible to execute the framework concurrently on more than one CPU.
- **Models of computation**: Gives a short introduction on the used models of computation (e.g. finite state machines, lambda calculus, petri nets)
- **Time model:** Indicates which time model is supported. Possible models are discrete event (DE), continuous time (CT), or for hybrid (H) for DE and CT.
- **Domain-agnostic**: Indicates if the framework is applicable in multiple domains (marked with “X”) or if it is developed for special domains (not marked).
- **Supported standards**: List of supported standards like FMI, HLA or MAS.
- **Supported platforms:** Name of operating systems & languages the frameworks can be executed with.

Framework	Developers	Active development	Licence needed	Open source	Monolithic	Distributable	Models of computation	Time model	Domain-agnostic	Supported standards	Supported platforms
CoppeliaSim	Coppelia Robotics GmbH	X	X			X	ODE, Vortex, Newton, Bullet	-		None	Linux
COSSIM	Synelixis Solutions Ltd. and research partners	X	X	X		X	-	DE	X	HLA	TinyOS
CyberRange	Airbus Cyber Security	X	X			X	Unknown	-		None	Windows
CPS Twinning	Matthias Eckhart, Andreas Ekelhart	X	X	X	X				X	None	independent
DACCOSIM NG	CentraleSupélec IDMaD research team, EDF R&D MIRE department in the RISEGrid Institute	X	X	X		X	Euler and Richardson	CT	X	FMI, HLA	Windows, Linux

Framework	Developers	Active development	Licence needed	Open source	Monolithic	Distributable	Models of computation	Time model	Domain-agnostic	Supported standards	Supported platforms
Dymola	Dassault Systèmes	X	X			X	ODE, DAE, bond graphs, Petri Nets, Finite State etc.	H	X	FMI	Windows
Eclipse Ditto	Bosch	X	X	X	X		Unknown	-	X	None	Independent
FlexSim	Flexsim Software Products Inc.	X	X				Unknown	DE	X	System C	Windows
FMI4j	NTNU Aalesund	X	X	X		?	Unknown	H	X	FMI	Platform independet, JVM
Gazebo	OSRF	X	X	X		X	ODE	-		None	Linux
gem5	University of Michigan and Wisconsin	X	X	X		X	AtomicSimple, TimingSimple, In-Order, O3	DE		System C	Windows, Linux, IBM, DEC
IBM Watson IoT	IBM	X	X			X	Unknown	-	X	FMI	Unknown
INTO-CPS	INTO-CPS Association	X	X	X		X	Unknown	H	X	FMI	Windows, Linux, Darwin
M3	TRIMEK	X	X			X	Finite State machines	CT	X	None	Windows, Linux, OSX
MasterSim	Institut für Bauklima der TU Dresden	X	X	X		X	Gauss-Jakobi, Gauss-Seidel, Newton Iteration, Variable Time Stepping	H	X	FMI	Windows, Linux, MacOS

Framework	Developers	Active development	Licence needed	Open source	Monolithic	Distributable	Models of computation	Time model	Domain-agnostic	Supported standards	Supported platforms
							and Size Control				
MECSYCO	University de Lorraine, Loria and Inria	X	X	X		X	Gauss-Seidel	DE	X	MAS, FMI, DEVS	Platform independent
MOKA	CEA, French Alternative Energies and Atomic Energy Commission, Pauline Deville	X	X			X	Finite State machines, Gauss-Seidel	H	X	FMI	Eclipse
MOSAIK	OFFIS	X	X	X		X	Unknown	DE		FMI, OPC UA, MAS	Windows, Linux, OSX
Microsoft Azure	Microsoft	X	X			-	Unknown	-		None	Unknown
OMSimulator	Linköping University	X	X	X		X	Unknown	DE	X	FMI	Windows, Linux, Mac
Plant Simulation	Siemens AG	X	X			X	Unknown	DE	X	None	Windows XP, Vista, 7, 8
PowerDEVS	Universidad Nacional de Rosario	X	X	X			Euler, Runge-Kutta	H	X	DEVS	Platform independent
Ptolemy II	Edward A. Lee, Janette Cardoso	X	X	X			Multiple	DE	X	FMI	Platform independent
PyFMI	Christian Winther	X	X	X		X	ODE	H	X	FMI	Platform independent
Roboguide	FANUC	X	X				Unknown	-		None	Windows
ROS	OSRF	X	X	X		X	Unknown	-		None	Linux

Framework	Developers	Active development	Licence needed	Open source	Monolithic	Distributable	Models of computation	Time model	Domain-agnostic	Supported standards	Supported platforms
Seebo Digital Twin	Seebo Interactive LTD	X	X				Unknown	-	X	None	Microsoft Azure
SimPy	Ontje Lünsdorf, Stefan Scherfke	X	X	X	X		Unknown	DE	X	None	Windows, Linux
simul8	Simul8 Corporation	X	X			X	Unknown	DE	X	None	Windows
Webots	Cyberbotics Ltd.	X	X	X		X	ODE	-		None	Linux
Wrld3d	WRLD	X	X	X		X	Unknown	-	X	None	Linux, Android, IOS

Table 2: List of simulation tools.

2.2.3. Overview of Existing Tools Regarding Simulation Frameworks

This section gives detailed information about the exiting tools from Table 2.

CoppeliaSim (previously V-REP)

CoppeliaSim is a robot simulator software with an integrated development environment, produced by Coppelia Robotics GmbH. It supports multiple physics engines and it offers a rich set of models including bipedal, hexapod, wheeled and flying robots. It provides a good API documentation and regular updates since 2013. The built-in editor is complete in features and intuitive.

Facts

- **Developers:** Coppelia Robotics GmbH
- **Active development:** yes, last commit 17.01.2020 https://github.com/CoppeliaRobotics/CoppeliaSimLib
- **Licence:** Apache
- **Open source:** dual license. Commercial non distributable for the full version. Free for educational purposes (excluding research)
- **Monolithic:** yes
- **Distributable:** dual license.
- **Models of computation:** ODE, Bullet, Vortex, Newton
- **Time model:**
- **Domain-agnostic:** no
- **Supported standards:** none
- **Supported platforms:** Linux

COSSIM

The developers of COSSIM claims it to be the first simulation framework for holistic system-of-systems simulation including processors, peripherals and networks[53]. This is done by integrating the gem5 simulator into OMNeT++. The node simulator modules of gem5 covers the processing and the OMNeT++ builds a network between the instances. The connection is based on interfaces according to the HLA standard. The energy consumption of each gem5 instance is estimated by McPat. In the COSSIM framework these nodes are called HLA-enabled nodes. They consist of two parts. One part is the network simulation and the other part is the communication via the HLA framework. The synchronisation has two steps, one per node and one global synchronization. This can be orchestrated with a GUI. The simulation framework has been validated in two real world applications, the Visual Search application and the Building Management System. By distributing the simulation on different CPUs they achieved quick simulation results and propose it as a framework for simulating large systems.

Facts

- **Developers:** Synelixis Solutions Ltd. and research partners
- **Active development:** yes, last commit 28.06.2019 https://github.com/H2020-COSSIM
- **Licence:** BSD2 & BSD3
- **Open source:** yes
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** unknown

[53] A. Brokalakis, N. Tampouratzis, A. Nikitakis, S. Andrianakis, I. Papaefstathiou, D. Pau, E. Plebani, M. Paracchini, M. Marcon, I. Sourdis, P. R. Geethakumari, M. C. Palacios, M. A. Anton and A. Szasz, “COSSIM: An Open-Source Integrated Solution to Address the Simulator Gap for Systems of Systems,” Prague, Czech Republic, 2018.

- **Time model:** DES
- **Domain-agnostic:** yes
- **Supported standards:** HLA
- **Supported platforms:** TinyOS

CyberRange Airbus

Airbus CyberRange is an advanced simulation platform that can be used to model IT / OT systems composed of tens or hundreds of machines and play realistic scenarios including real cyber-attacks. The platform manages several environments, isolated ones from the others, as well as from the legacy IT / OT from the organization.

By means of these capabilities, users can immerse themselves in an environment customized to look like their system in operation. This support several use cases including operational qualification, testing, and training.

For the hardware, the tool exists in two main forms:

- Physical platform: High performance servers stored in a mobile box, on site, switches, hosting VMware, vSphere Infrastructure.
- Cloud Platform: the CyberRange platform is also available in the Cloud, allowing a flexible and multisite collaborative experience.

To use the hardware, Airbus CyberSecurity has developed the software LADE: set of web and micro services simplifying the deployment of virtualized infrastructures, running cyber-attacks, tests and scenarios. LADE allows hybrid infrastructures management. This management software significantly reduces the delay between designing the simulation and having it deployed.

Main Capabilities

The aim of CyberRange is a realistic simulation environment "at your hand" to use or create large IT / OT systems (virtual or hybrid) and reproduce a realistic activity (traffic or cyber-attack).

For this goal, there are:

- Modelling real or representative systems
  - Import or create complete systems (IT or OT)
  - Manage large scale systems composed of hundreds of machines
  - Integrate physical device into “hybrid network
- Embedded network traffic generator:
  - Animate the representative system
  - Emulate activities (with a reproduction of a human activity on the system)
- Automated incident scenario generation
  - Orchestrate complex chain of events
  - Operate autonomously
- Set of configurable attacks (security incidents) ready to use
  - Launch attacks directly from the interface
  - Configure attacks from the GUI

The CyberRange allows work optimisation for:

- Import Virtual Machine
  - Compatibility with standard virtualization technologies (VMware and Docker)
  - Integrate VM templates or Docker Containers in libraries so it can be re-used easily
- Semi-automatic networks configuration
  - 1 click network configuration from the graphical interface
  - First level of configuration available from the GUI
- Backup and deployment of topologies
  - Capitalize on modelling work by creating reusable topologies et roll them out « on the fly »
  - Integrate topologies in libraries so it can be re-used easily
- Configuration & management of IT Stock
  - Topological view of VM & physical equipment
  - VM & network monitoring from the administration
  - Screen deport and/or command console to access each machine
  - Centralizing software updates for machines deployed in different workspace

For the collaborative work, technical base "shared" to work as a team on the same project simultaneously or to exchange resources (machine templates, topologies, and scenario can be exported and imported).

Multiple users can work together in the same work zone with a light client accessible from all user machines.

For different projects that should not communicate, the management of work zones is isolated. There is no interference between different works or projects and isolated from organization's IT.

Finally user rights are managed in details:

- access to workspaces,
- access to contents,
- visibility of each machine of a network deployed in a workspace,
- by user or by groups.

Architecture

The CyberRange is a standalone solution which does not require integration with the existing IT / OT nor an internet access. The platform itself is a shared technical base enabling organization's teams to work together or share resources (such as machine templates, topologies or scenarios). The CyberRange core simulation capabilities and advanced features can be leveraged to serve use cases – such as training or testing – meeting organization operational needs. In order to meet the constraints of a complex environment, the platform is open to be interfaced with external equipment such as a physical industrial control system, a hardware traffic generator or a real physical or virtual system.

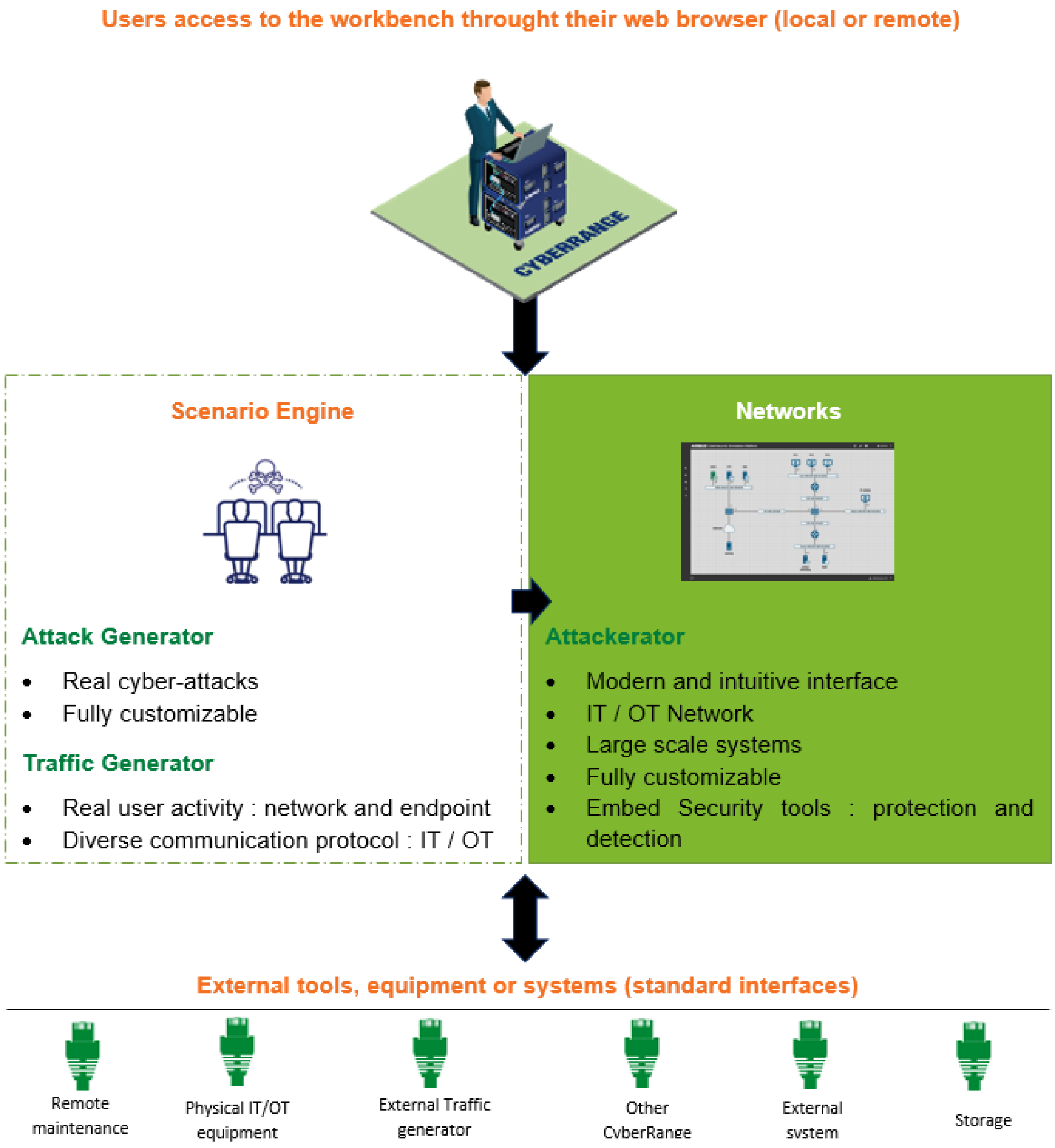


Figure 3: Overview CyberRange.

The CyberRange is used for different use-cases: operational exercises, training, test and operational qualification

Hardware description

The CyberRange uses high efficiency servers to host and run one or more virtualised networks with thousands of Virtual Machines and Containers.

The standard form factor is CyberRange CR8 platform providing 8 working environments (work zones), each work zone offers a capacity of 25 VMs and 100 containers, thus offering a potential virtualisation, combined of 200 virtual machines and 800 Dockers.

Scalability

The CyberRange platform can be scaled up at different levels: Network – Servers – VMware – LADE.

It is possible to add switches to be able to interconnect more than 24 physical devices. At a switch level, the concept of “stack” can be used, allowing administration at the same time. Network capacity expansion requires switches that can address VLANs greater than 1024 as well as switches that can declare a large number of VLANs (for example 4096). It is possible to add several servers running the VMware ESXi operating system in the VMware Cluster. LADE software acts at the cluster level, which means that the number of servers underlying the cluster is completely transparent. The deployment limits of the software LADE are those of VMware. The limits of the various VMware entities are available on the VMware site.

Mobility and Autonomy for physical CyberRange

The Airbus CyberSecurity platform is designed to be an autonomous platform:

- It does not depend on any external software or material to function
- It does not require permanent Internet connection
- It needs only one electrical connection

In addition, customer will be completely autonomous from Airbus CyberSecurity in its everyday use of the CyberRange. Airbus CyberSecurity will ensure in particular the capacity of action in total autonomy of the customer’s teams.

Hybrid platform (physical CyberRange)

Physical equipment can be connected to the platform through the ports of the switch and integrated into a virtualized network hosted on CyberRange. The CyberRange comes with a switch in order:

- To connect physical equipment, IT or OT
- To connect hardware traffic generators
- To be inter-connected with other existing platforms or systems
- To be inter-connected with storage systems
- To accept connections of remote maintenance and remote access in web mode
- To inter-connect several CyberRange environments together

Cloud CyberRange

In some use-cases, it is necessary or simpler to be able to access the different tools available in the CyberRange. Using cloud services, Airbus CyberSecurity has developed the features to have CyberRange as SaaS.

Software description – LADE V2.6

User Interface

Airbus CyberRange is delivered with the software LADE, developed by Airbus CyberSecurity. Current version is 2.6. It is designed to simplify the implementation of complex information systems and to automate the execution of commands on these information systems. As a web client, the software LADE is available through a web browser, reducing the need of access endpoint maintenance.

Main interfaces are:

- A User interface, used to access the network builder and the scenario builder and carry out a set of operations (creation, modification, access to the topology, training exercise, etc.). The GUI has been developed to perform very complex operations in an easy and visual way
- An Administration interface for content management (VM library, topology, attack, etc.), user/group management and technical incident management
- Advanced functions for advanced users (CLI client, VMWare interface, API)

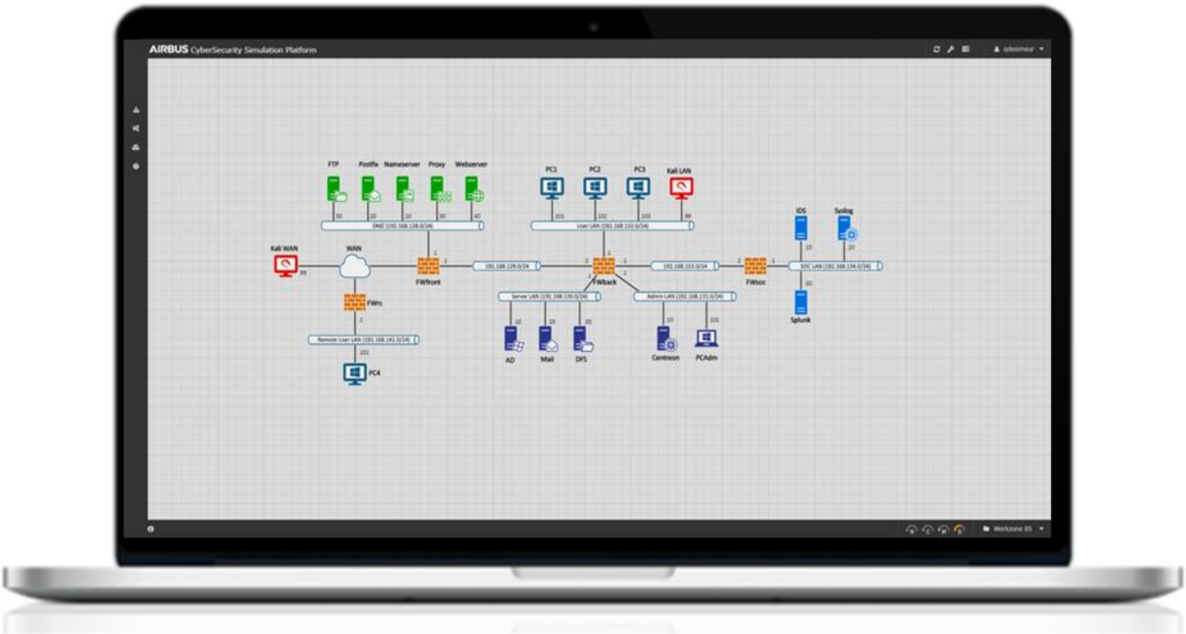


Figure 4: The workbench is the main user interface.

This user interface is composed of the following modules:

- In the centre, the work zone for viewing and interacting with virtual infrastructures.
- On the left, the navigation menu.
- At the bottom right, the drop-down menu for selecting one of the work zones.
- At the bottom left, the real-time event area providing information on the actions performed in the current work area.
- At the top right, buttons to access the administration interface and manage tasks in the current workspace.

Multiple work zones

The CyberRange offers independent work zones which represents a virtual environment dedicated to a user or a group of users. As a fully customizable platform, the Airbus CyberRange graphical user interface allows users to customize their working environment, add notes and key commands lines to help them pursue exercises.

Each work zone is totally isolated from the other work zones, so the actions of one participant do not interfere with the other participants working on other work zones. Each work zone can accommodate standalone replicas of a network architecture or information systems.

Interconnecting work zones is possible by connecting a firewall or router in each zone to a shared zone.

Simulation Capabilities

The CyberRange enables virtualisation of complex networks including:

- Operating Systems (OS): Debian, CentOS, Ubuntu, Windows, etc.
- Servers: Windows Server, File sharing (FTP), Web Servers (apache, nginx), Databases (MariaDB, Postgres), etc.
- Security equipment: firewall, Intrusion Detection System (IDS), etc.
- Sub-network zones: DMZ, User LAN, etc.
- Network architectures: Virtual switch, Virtual routers, VLAN, AS, BGP, OSPF, RIP VRRP, Network operators, Backbone, etc.

From the software perspective, the network frames are managed by the virtual component of VMware by a VMware Distributed Virtual Switch. This component creates virtual networks associated with a VLAN number, and from which the virtual machines are connected.

LADE ensures storage consumption limits both per group of users and per work zone. VMware ensures computing limits (CPU usage, RAM usage). Those limits guarantee dedicated performances in all work zones. Resource limitation mechanisms are customisable in VMware for virtual machines and in LADE for Docker containers. LADE has a library of architectures, limited by the allocated disk space.

Extending this space is easy by connecting the platform with external storage systems such as an NAS.

In addition to computing capacity, each work zone can have up to 32 networks, completely independent and isolated from the other spaces using VLANs.

Deploying a virtual machine or container is done by drag-and-drop to the workspace. The user can change the configuration settings before creating the component in his workspace.

Networks

The creation of Networks is carried out via a Drag-And-Drop mechanism by selecting a component from the Network section.

The control panel proposes to set the network addressing the default gateway for all the machines that connect to it. Once deployed, the context menu allows the removal or the configuration of the selected network such as the network description, name, address and the default gateway.

To connect a host to the network, simply click on it, then click on the network to which you want to connect it. A control panel opens to define the network settings. In the same way, a user can modify or delete the network connection of a machine via the context menu.

External Hosts

The CyberRange offers the possibility to register an External Host. This feature enables the user to connect a physical device to the switch of the CyberRange and configure the host directly from LADE.

The icon library proposes a range of images that best represents the physical equipment interconnected to the platform.

The switch dedicated to the interconnection of physical devices with RJ45 Ethernet links workstations, network devices, and more components in virtualised network architectures.

For equipment that does not have an Ethernet interface such as sensors or other IoT devices and that still have to be connected to the CyberRange, it is possible to connect them via an intermediate Wi-Fi router, for example, as illustrated by the diagram below:

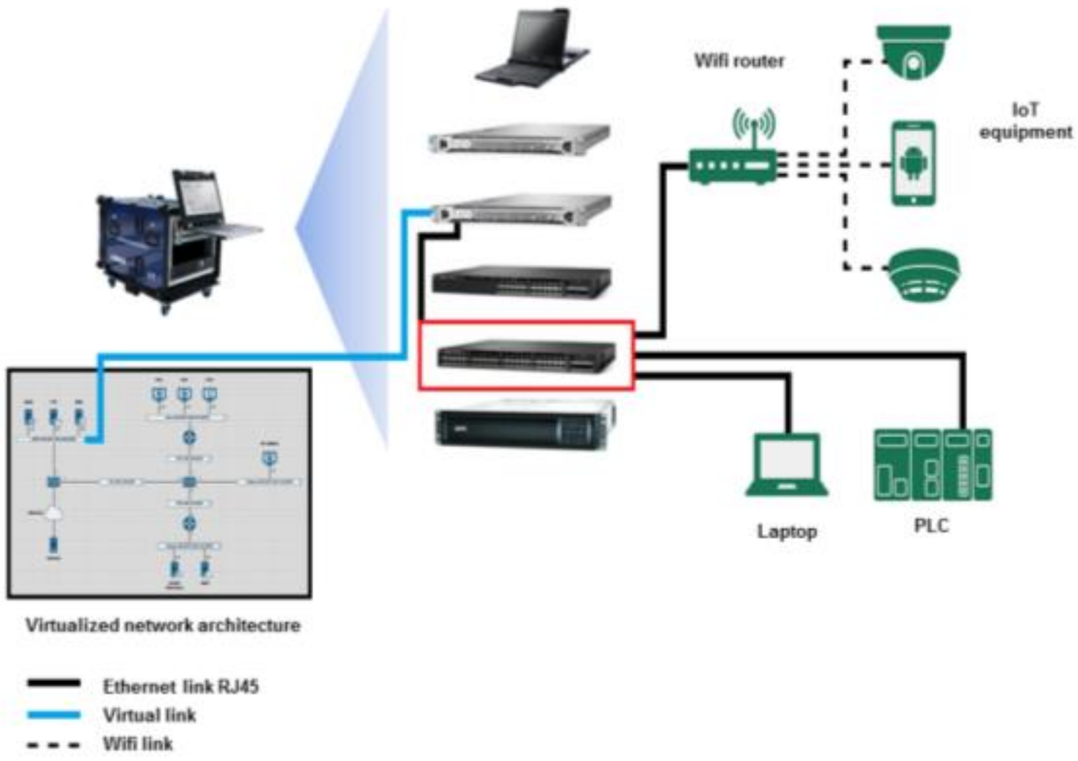


Figure 5: Interconnection capability.

In order to interconnect and represent the physical device in the network virtualized in a work zone, the LADE offers to specify the hostname of the physical equipment and various advanced options. It is also possible to configure a port in "mirroring" mode, which can be useful to connect a network probe to the platform so it can observe all the network traffic passing over a virtual network.

Topologies

A user can also perform group actions on machines, such as backing up part of the infrastructure as a topology.

Once built, the user can select all or part of the system to save it as a new component. It is then directly inserted into the library and can be reused at will, either in the same work zone or in a different work zone. The copy becomes accessible by simple drag-and-drop. It is possible to modify and save this component again, while keeping the previous version. This makes it possible to obtain several versions of the component, and to use the one that is most appropriate when needed. Once the topology is saved, it appears in the Topologies section of the navigation panel.

Attacks

The software LADE offers the possibility to launch attacks on a virtualized topology. The CyberRange platform integrates a set of attacks.

Execution conditions of the attacks (source, destination, frequency and any specific parameters) can be set by the user. The administrator can add/modify attacks from the administration interface. They can also export/import attacks to make them available to users.

Traffic Generators

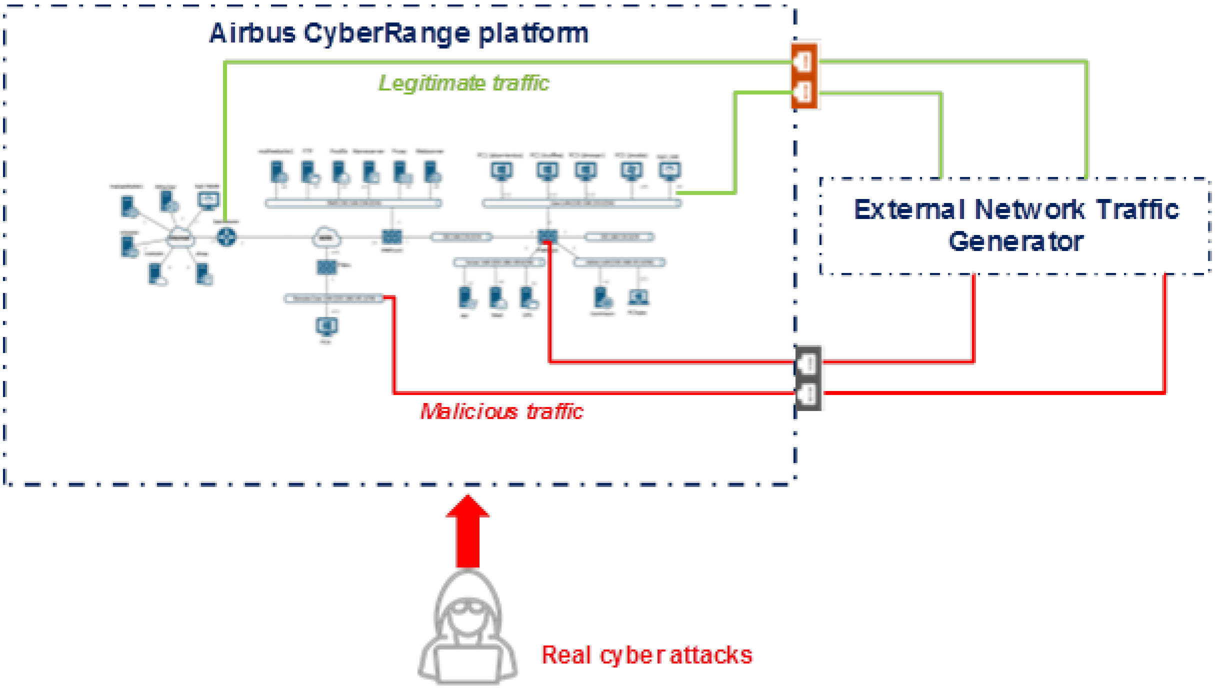
The software LADE offers the possibility to run traffic generators on a virtualized topology. The CyberRange platform integrate a set of network traffic generators able to generate random flows and reproduce traffic recorded in virtualized infrastructure. Execution conditions of the traffic generators (source, destination, frequency) can be set by the user. The administrator can add/modify traffic generators from the administration interface. They can also export/import generators to make them available to users.

The CyberRange platform offers the possibility to replay recorded traffic in virtual infrastructures, via LADE interface, in the same way as the other items of the catalogue (network and life traffic, attacks, etc.). During the execution of the generator, the user can view the operations performed by the traffic generator, as in the example of the HTTP traffic generator given below:

External Traffic Generator

The CyberRange platform also offers the possibility to connect hardware equipment in order to target physical networks and other physical equipment. Airbus CyberSecurity provides a Network Traffic Generator.

The combination of an external traffic generator and the Airbus Cyber Range platform allows the user to work in a realistic environment. With the external hardware providing a real legitimate network flow, the user can play real cyber-attacks thanks to the Airbus CyberRange platform.



Scenarios

The CyberRange platform provides pre-configured scenarios. The platform also supports the creation of new scenarios as well as the customization of existing scenarios.

Airbus CyberRange also supports various triggering modes in order to adapt to the variety of users' levels and to provide the most realistic formats, adapted to different use cases.

Creation of Attacks, Traffic Generators and Scenarios

Creating an action or a scenario is possible from the GUI or the CLI, it is saved in JSON format with optional files (executable, script, attachment, etc.) useful for running them.

Attacks, Traffic Generators and Scenarios can be imported / exported as JSON files. This format is used to represent the information in a structured textual manner, just as XML does for example.

CyberRange and CyberFactory#1 Project

With the work to be carried out in the CyberFactory#1, it is to innovate and improve the capabilities in OT simulation.

The CyberRange allows creating virtual machine for OT network. But the graphics capabilities are limited. For OT simulation, the process must be visible by users as close as reality. The new functionality requires:

- hardware modification to incorporate graphic card,
- create new features to be able to distribute the capabilities of graphics processing unit in the virtual machines
- enable the integration of digital twins of cyber-physical equipment typical of factory shop-floor such as robotic arms,
- simulate the impacts of network events on cyber-physical assets and related industrial processes

- quantify such impacts so as to assess the overall balance between cost of attack and cost of countermeasures
- enable (by the above measures) to test and validate OT network architectures from a security perspective in virtual environment prior to life-scale deployment

One of the challenges is to implement user friendly graphic capabilities.

Moreover, to be able to create a simulation a digital twin of OT process, the CyberRange must be developed to allow integration of simulator from different providers. The different simulators must communicate as their physical representation. The objective is to be able to have simulated components which can word with physical components in a topology. For example, if there is a physical PLC, we can plug it on the CyberRange enabling communication with a simulator robot. If there is no physical PLC, a simulator PLC could be used.

For the cloud CyberRange, the challenge is to create the capability to connect the physical OT component with the simulation which works in cloud.

With the features, the ambitions are to develop cybersecurity simulation for the training or products testing from the shop floor to the data lake.

Facts

- **Developers:** Airbus Cyber Security
- **Active development:** yes
- **Licence:** proprietary
- **Open source:** no
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** no
- **Supported standards:** none
- **Supported platforms:** Windows

CPS Twinning

CPS Twinning is a framework for generating and executing digital twins that mirror cyber-physical systems[54]. It generates DTs based on the specification of CPS. It is a proof of concept that can be used as first approach to model some environments, but also have some limitations such as generating digital twins for wireless devices[55]. On the right hand of Figure 6 you see the Generator and Virtual Environment which are the main modules of CPS Twinning.

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[54] "CPS Twinning," [Online]. Available: https://github.com/sbaresearch/cps-twinning. [Accessed 04 2020].

[55] M. Eckhart and A. Ekelhart, "A Specification-Based State Replication Approach for Digital Twins," 2018.

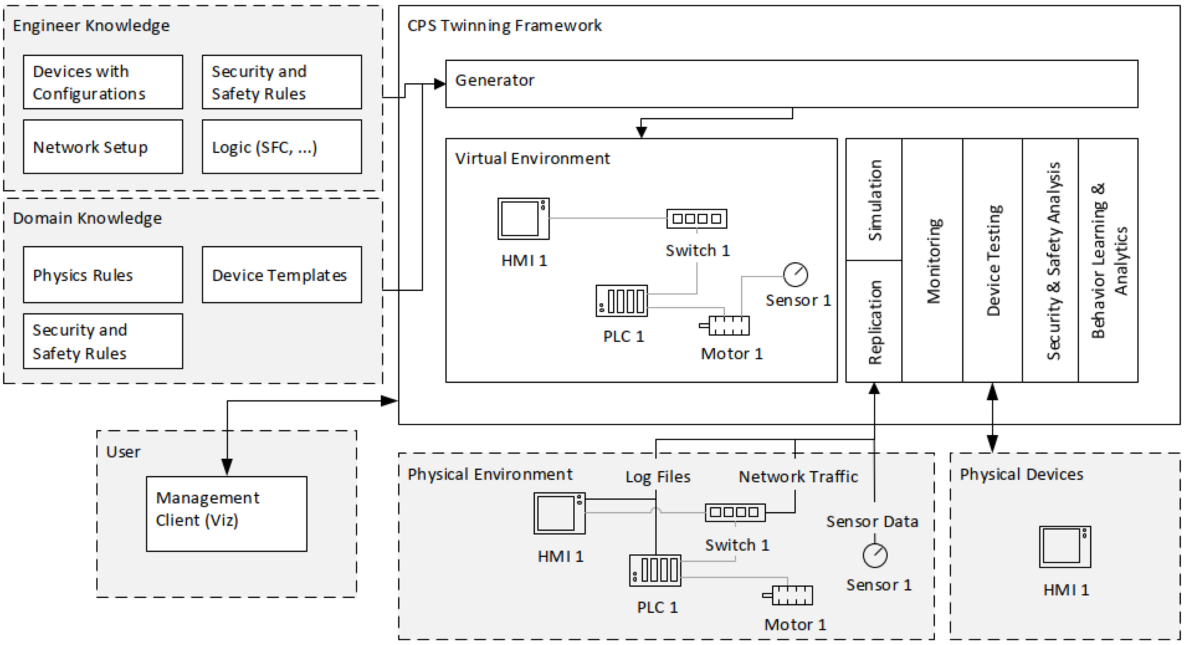

Figure 6: Architecture of CPS Twinning[56].

The input of the Generator is engineer and domain specific knowledge. With that input it generates the virtual environment. The created virtual environment can run in an independent mode or act as a recorder to replicate the actual state of the physical domain.

Facts

- **Developers:** Matthias Eckhart, Andreas Ekelhart
- **Active development:** yes, 07.09.2019
  https://github.com/sbaresearch/cps-twinning
- **Licence:** MIT
- **Open source:** yes
- **Monolithic:** yes
- **Distributable:** unknown
- **Models of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** yes
- **Supported standards:** none
- **Supported platforms:** platform independent

DACCOSIM NG

DACCOSIM NG is an environment to develop and run co-simulation use cases supported by JavaFMI, a suite of tools for interoperability using the co-simulation part of FMI standard. DACCOSIM allows the design and execution of co-simulations, providing mechanisms to define co-simulation graphs composed of blocks (mainly FMUs). As stated the FMI only

[56] M. Eckhart and A. Ekelhart, “A Specification-Based State Replication Approach for Digital Twins,” 2018.

provides a standardized interface without an orchestrating master code. The DACCOSIM NG delivers a master functionality that uses logical and potentially distribute FMUs on different computation nodes[57]. Afterwards the graphs are translated into a data structure, transferred to an optimized master code developed in Java in conformance with the features described in the FMI-CS standard[58].

Facts

- **Developers:**
  - Jean-Philippe Tavella (EDF Lab Paris-Saclay, France)
  - Dr José Évora-Gómez (Monentia, Las Palmas de GC, Spain)
  - Pr Stéphane Vialle (LRI, GeorgiaTech-CNRS, CentraleSupelec, Université Paris-Saclay, France)
  - Dr José-Juan Hernández (SIANI, Universidad de Las Palmas de Gran Canaria, Spain)
  - Dr Mathieu Caujolle (EDF Lab Paris-Saclay, France)
  - Dr Enrique Kremers (EIFER, European Institute for Energy Research, Germany)
- **Active development:** yes, last commit 11.03.2020 https://bitbucket.org/simulage/daccosim/
- **Licence:** GNU
- **Open source:** yes
- **Monolithic:** no
- **Distributable:** yes[59]
- **Models of computation:** Euler and Richardson[60]
- **Time model:** CT
- **Domain-agnostic:** yes[61]
- **Supported standards:** FMI-CS (FMI for co-simulation), HLA
- **Supported platforms:** Windows, Linux

Dymola

Dymola (**Dy**namic **Mo**delling **La**boratory) is a simulation environment based upon the object oriented modelling language Modelica. Dymola claims to be the most powerful and flexible modeling and simulation environment for Modelica today. It offers the user a

[57] V. Galtier, S. Vialle, J.-P. Tavella, J.-P. Lam-Yee-Mui und G. Plessis, «FMI-Based Distributed Multi-Simulation with DACCOSIM,» Society for Modelling & Simulation International (SCS), Alexandria, USA, 2015.
[58] J.-P. Tavella, J. Évora-Gómez, J. Hernández-Cabrera und S. Vialle, «DACCOSIM NG 2018 USERS GUIDE,» Monentia, 2018.
[59] C. Gomes, C. Thule, D. Broman, P. G. Larsen und H. Vangheluwe, «Co-simulation: State of the art,» 2017.
[60] V. Galtier, S. Vialle, J.-P. Tavella, J.-P. Lam-Yee-Mui und G. Plessis, «FMI-Based Distributed Multi-Simulation with DACCOSIM,» Society for Modelling & Simulation International (SCS), Alexandria, USA, 2015.
[61] J.-P. Tavella, J. Évora-Gómez, J. Hernández-Cabrera und S. Vialle, «DACCOSIM NG 2018 USERS GUIDE,» Monentia, 2018.

homogeneous tool for efficient validation and optimization of complex systems. With Dymola models can be created, tested, simulated and reconfigured[62].

Dymola is modular and consists of a standard configuration including the Modelica Standard Library, which can be extended with options and additional libraries.

The Dymola standard includes[63]:

- Graphical model editor
- The Modelica interpreter
- Symbol processor and model translator
- Simulator
- Graphical output
- HTML model documentation generator

Facts

- **Developers** : Dassault Systèmes
- **Active development**: yes, last commit 29.11.2019
- **Licence**: proprietary
- **Open source**: no
- **Monolithic**: no
- **Distributable**: yes
- **Models of computation**: ODE, DAE, bond graphs, finite state automata, Petri nets and more
- **Time model:** DE, CT, hybrid
- **Domain-agnostic**: yes
- **Supported standards**: FMI
- **Supported platforms**: Windows

Eclipse Ditto

Eclipse Ditto is a digital twin developed by Bosch. It enables the design of digital twins in a form of IoT development patterns. It can be seen as an open source foundational layer of Bosch IoT platform[64]. For the developers digital twins are mainly a mechanism for simplifying IoT solution development[65]. So the focus of Eclipse Ditto is to provide APIs for web applications, mobile applications or other backend services, see Figure 7.

[62] Dassault Systèmes, [Online]. Available: https://www.3ds.com/de/produkte-und-services/catia/produkte/dymola/. [Accessed 20 04 2020].
[63] http://www.cenit.com/de_DE/produkte-loesungen/plm/dassault-systemes/plm-software/dymola.html
[64] "Eclipse Ditto," [Online]. Available: https://www.eclipse.org/ditto/. [Accessed 04 2020].
[65] https://blog.bosch-si.com/developer/how-digital-twins-boost-development-in-the-iot/

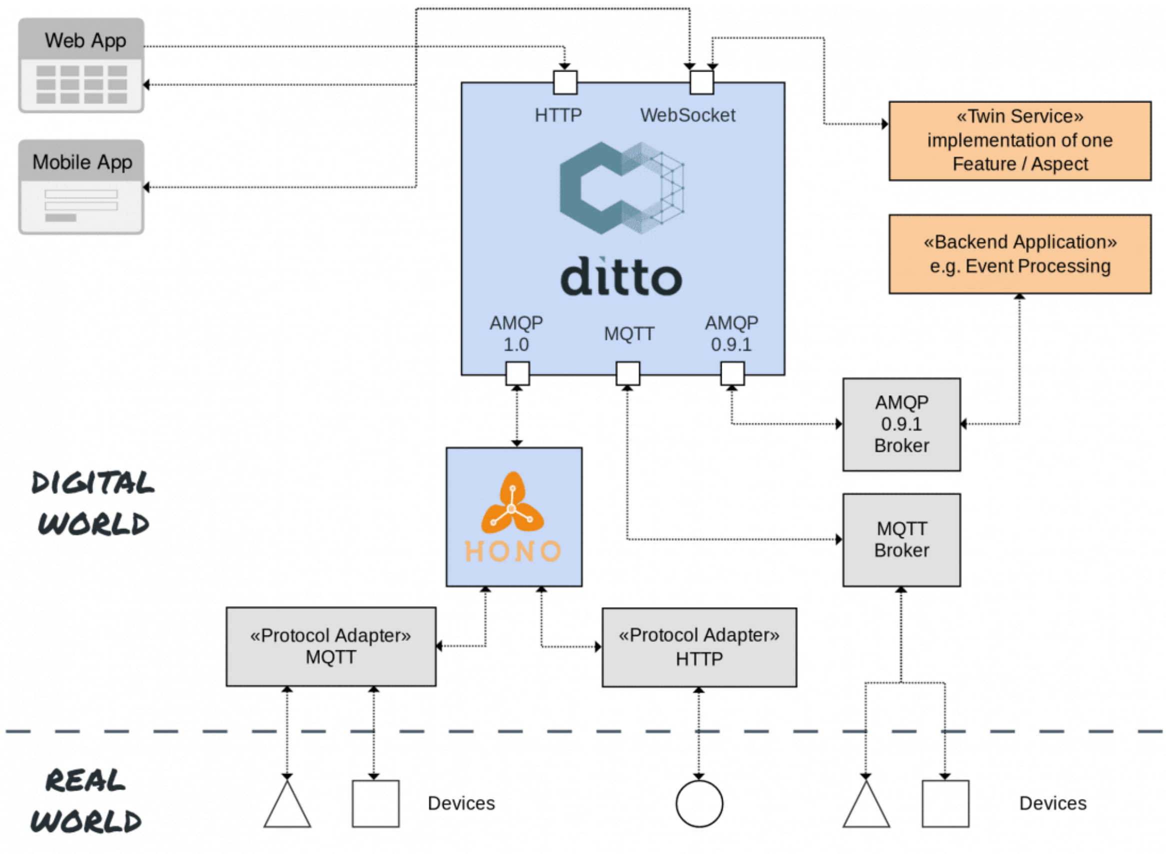

Figure 7: Overview of Ditto Architecture[65].

Facts

- **Developers:** Bosch
- **Active development:** yes, last commit 22.04.2020 https://github.com/eclipse/ditto
- **Licence:** EPL 2.0
- **Open source:** yes
- **Monolithic:** yes
- **Distributable:** unknown
- **Models of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** yes
- **Supported standards:** none
- **Supported platforms:** platform independent

FlexSim

FlexSim is an object-oriented software architecture for simulating and modelling process activities at real-time with a graphical interface for animation. The concept consists of a FlexSim compiler, a FlexSim developer and some FlexSim applications[66]. As programming

[66] W. B. Nordgren, “FLEXSIM SIMULATION ENVIROMENT,” Orem, USA, 2003.

language C++ or flexscript can be used. It allows the user to construct a 3D computer model for experimenting[67].

On the homepage[68] the manufacturer gives information that FlexSim can be used as engine driving simulation technology for digital twins in smart factories.

Facts

- **Developers** : Flexsim Software Products Inc.
- **Active development**: yes, last commit 2019
- **Licence**: proprietary
- **Open source**: no
- **Monolithic**: no, software can run in different instances and be connected through TCP/IP, however timing issues can happen
- **Distributable**: no
- **Models of computation**: unknown
- **Time model:** DES
- **Domain-agnostic**: yes
- **Supported standards**: SystemC
- **Supported platforms**: Windows Vista, 7, 8, 10

FMI4j (Java)

FMI4j is a software package for implementing FMUs on the Java Virtual Machine (JVM). The software package is written in Kotlin. The developer claim FMI4J to be faster than other available FMI implementations. The package consists of the following three components[69]:

1. **FMI-Modeldescription:** A library for parsing the meta-data found in the modelDescription.xml located within an FMU
2. **FMI-Import:** A library for loading and running FMUs on the JVM. Supports FMI 2.0 for CS and ME
3. **FMU2Jar**: A command line tool for turning an FMU into a Java library (.jar)

Facts

- **Developers**: By researches at the NTNU Aalesund
- **Active development**: yes, last commit 05.02.2020 https://github.com/NTNU-IHB/fmi4j
- **Licence**: MIT-Licence
- **Open source**: yes
- **Monolithic**: no
- **Distributable**: unkown
- **Models of computation**: unknown
- **Time model:** DES, CTS, hybrid

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[67] J. M. Garrido, Object Oriented Simulation, Georgia: Springer, 2009.
[68] FlexSim Software Products, Inc, “FlexSim problem solved.,” [Online]. Available: https://www.flexsim.com/digital-twin/. [Accessed 17 04 2020].
[69] W. B. Nordgren, “FLEXSIM SIMULATION ENVIROMENT,” Orem, USA, 2003.

- **Domain-agnostic**: yes
- **Supported standards**: FMI
- **Supported platforms**: platform independent, but needs JVM

Gazebo

Gazebo is the simulation environment integrated in the ROS framework. It is actively maintained by the Open Source Robotics Foundation so it is focused on the robotic field. It is an open source project with an active community. It has become a very popular simulation tool in the robotics community, although the interfaces are not as user friendly as in commercial simulators. Gazebo supports several physics engines and is suitable for the simulation of any robot, including the class of very complex humanoid robots. The current releases are stable and can easily be extended with new functions due to their modular design. The integration with ROS allows to execute the same code in the simulation and on the real robot.

Facts

- **Developers:** Open Source Robotics Foundation
- **Active development:** yes, last commit 21.04.2020
  https://bitbucket.org/osrf/gazebo/
- **Licence:** Apache
- **Open source:** yes
- **Monolithic:** yes
- **Distributable:** yes
- **Models of computation:** ODE
- **Time model:** unknown
- **Domain-agnostic:** no
- **Supported standards:** none
- **Supported platforms:** Linux

gem5

The gem5 simulator is a modular platform and based on the m5 simulation framework and GEMS[70]. M5 is used for research purposes in TCP/IP networks[71]. GEMS is a modular simulation infrastructure to decouple simulation functionality and timing to evaluate multiprocessor systems. The goal is to leverage the efficiency and the robustness of functional simulators[72]. Both systems are not looked at in particular because they are implemented in the further developed gem5 simulator. The gem5 is widely used in

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[70] N. Binkert, B. Beckmann, G. Black, R. K. Steven, A. Saidi, A. Basu, J. Hestness, D. R. Hower, T. Krishna, S. Sardashti, R. Sen, K. Sewell, M. Shoaib, N. Vaish, M. D. Hill and D. A. Wood, “The gem5 Simulator,” New York, USA, 2011.
[71] N. L. Binkert, R. G. Dreslinski, L. R. Hsu, K. T. Lim, A. G. Saidi and S. K. Reinhard, “The M5 Simulator: Modeling networked systems,” Michigang, USA, 2006.
[72] M. M. K. Martin, D. J. Sorin, B. M. Beckmann, M. R. Marty, M. Xu, A. R. Alameldeen, K. E. Moore, M. D. Hill and D. A. Wood, “Multifacet´s General Execution-driven Multiprocessor Simulator (GEMS) Toolset,” Wisconsin, USA, 2015.

academics and in industry research of ARM and AMD. AMD uses gem5for design space exploration[73]. gem5 supports co-simulation since 2014 in a SystemC environment.

Facts

- **Developers:** University of Michigan (M5) and University of Wisconsin (GEMS)
- **Active development:** yes, last commit 15.04.2020 https://gem5.atlassian.net/projects/GEM5/
- **Licence:** BSD
- **Open source:** yes
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** AtomicSimple, TimingSimple, In-Order, and O3
- **Time model:** DES[74]
- **Domain-agnostic:** no
- **Supported standards:** SystemC
- **Supported platforms:** x86 (Windows), Alpha (DEC), ARM (Linux), MIPS (Linux), Power (IBM), Sparc (Linux)

IBM Watson IoT

IBM also developed a DT framework that help companies to virtually create, test, build and monitor a product reducing the latency in the feedback loop between design and operation. IBM understands a DT as a virtual representation of the elements and the dynamics of an IoT devices throughout its lifecycle. The real-time insights offered by digital twins makes it easier to identify and fix problems and get products to market faster[75].

Facts

- **Developers:** IBM
- **Active development:** yes
- **Licence:** commercial
- **Open source:** no
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** yes
- **Supported standards:** FMI
- **Supported platforms:** unknown

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[73] C. Menard, J. Castrillon, M. Jung and N. Wehn, “System Simulation with gem5 and SystemC,” Pythagorion, Greece , 2017.
[74] J. Lowe-Power, “gem5,” [Online]. Available: https://www.gem5.org/documentation/learning_gem5/introduction/. [Accessed 21 04 2020].
[75] “Digital twin: Helping machines tell their story,” [Online]. Available: https://www.ibm.com/internet-of-things/trending/digital-twin. [Accessed 04 2020].

INTO-CPS

The INTO-CPS application was developed by the INTO-CPS project from 2015 to 2017 as an integrated "tool chain" for comprehensive Model-Based Design (MBD) of CPS[76]. It is suitable for the overall development process from requirement engineering to realization in hard- and software. They cover several capabilities:

- Modeling and Simulating Mechatronic system
- Offers co-simulation orchestration engine (COE)
- Modeling and simulation management and environment
- FMI support and FMU import and export

Facts

- **Developers:** INTO-CPS Association
- **Active development:** yes, last commit 08.04.2020 https://github.com/INTO-CPS-Association/into-cps-application/commits/development
- **Licence:** no – (for non-Commerical usage)
- **Open source:** yes
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** unknown
- **Time model:** DE, CT, hybrid
- **Domain-agnostic:** yes
- **Supported standards:** FMI
- **Supported platforms:** Windows, Linux, Darwin

M3 (C++)

M3 software is a high performance metrological software developed by Innovalia Metrology for the capture and analysis of point clouds. M3 solves the complex process of scanning and managing point clouds in an agile, powerful and simple way. Pieces are scanned with M3 and points' cloud are bring out that enables to work with the digital twin with a representation of a high fidelity surfaces, M3 can be used with touching probes or optical sensors indistinctly. Some of M3 software advantages are:

- M3 is compatible with various 3D measuring devices
- Multisensor: Same workflow for optical and contact measurement
- Connect and Measure: M3 is very easy to use. Start working in a few minutes
- Traceability: Access your original information at any time
- Powerful information analysis

M3 software is only run in CMMs as a supporting system for driving the measuring analysis. This measures can be done with the help of a CAD file or it can be measured also a piece without the CAD file tracking the piece with three reference points. M3 software can run

[76] "Integrated Tool Chain for Model-based Design of Cyber-Physical Systems," Into-CPS association, [Online]. Available: https://into-cps.org/. [Accessed 17 04 2020].

simulations with CCMs preselected, there is no wide variety to choose inside the software, these simulations return the position of the measuring points with the time that have last.

Facts

- **Developers:** TRIMEK
- **Active development:** yes, last commit 14.01.2020 https://m3.innovalia-metrology.com/es/
- **Licence:** proprietary
- **Open source:** no
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** Finite state machines
- **Time model:** CT
- **Domain-agnostic:** yes (multiple domains)
- **Supported standards:** none
- **Supported platforms:** Linux, OSX, Windows

MasterSim

MasterSim is a co-simulation master program that supports FMI co-simulation. It couples different simulation models and exchanges data between simulation slaves at runtime.

MasterSim consists of a graphical user interface (GUI) and a command line simulator program "MasterSimulator". The separation between user interface and simulator enables the use of MasterSim in a scripted environment.

The Supported FMI Types are "FMI for co-simulation version 1" and "FMI for co-simulation version 2", asynchronous FMU types are not supported[77].

Facts

- **Developers:** Institut für Bauklimatik der TU Dresden
- **Active development:** yes, last commit 12.03.2020 https://sourceforge.net/projects/mastersim/ https://bauklimatik-dresden.de/mastersim/html_en/MasterSim_manual.html
- **Licence:** LGPLv3
- **Open source:** yes
- **Monolithic:** no
- **Distributable**: yes
- **Models of computation**: Gauss-Jakobi, Gauss-Seidel, Newton Iteration, Variable Time Stepping and Size Control
- **Time model:** DES, CTS, hybrid
- **Domain-agnostic**: yes
- **Supported standards**: FMI
- **Supported platforms**: Windows, Linux, MacOs

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[77] https://bauklimatik-dresden.de/mastersim/html_en/MasterSim_manual.html /. [Accessed 23 04 2020].

MECSYCO

Multi-agent **E**nvironment for **C**omplex **SY**stem **co**-simulation (MECSYCO) is a co-simulation tool based on the **D**iscrete **E**vent **S**ystem **S**pecification (DEVS) for complex systems. By using the multi-agent architecture different components are added to the simulation[78]. Each model corresponds to an agent, and the data exchange between the simulators correspond to the interactions between them. Moreover the co-simulation of the system corresponds to the dynamics of interaction between agents.

A co-simulation is conducted by MECSYCO with four concepts[79]:

1. A target system is partially represented by a **model** $\mathbf{m_i}$. This model hast input and output ports.
2. An **m-agent** $\mathbf{A_i}$ is responsible for the interaction and management of the m_i.
3. A **model artefact** $\mathbf{I_i}$ which acts as DEVS wrapper for a m_i
4. The interaction of A_i are realized by a coupling **artefact** $\boldsymbol{C_j^i}$

There is a possibility of FMU-Wraps but it needs information about continuous behaviour (already within FMU), state events detector and discrete behaviour component.

Facts

- **Developers:** MECSYCO is a common project between Université de Lorraine, LORIA and Inria
- **Active development:** yes, last commit 18.01.2018
- **Licence:** AGPLv3
- **Open source:** yes
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** Gauss-Seidel
- **Time model:** DES
- **Domain-agnostic:** yes
- **Supported standards:** MAS, FMI, DEVS
- **Supported platforms:** Java and C++ based version

MOKA

The MOKA framework is a software tool to provide an object orientation for FMU development. In contrast to other FMU tools like Matlab/Simulink, ScilabXcos or Modelica it doesn't use blocks or ports. While Aslan et al introduces the general concept of the

[78] B. Camus, T. Paris, J. Vaubourg, Y. Presse, C. Bourjot, L. Ciarlette und V. Chevrier, «MECSYCO: a Multi-agent DEVS Wrapping Platform for the Co-simulation of Complex Systems,» Villers-lès-Nancy, France, 2016.

[79] B. Camus, T. Paris, J. Vaubourg, Y. Presse, C. Bourjot, L. Ciarletta and V. Chevrier, "Co-simulation of cyber-physical systems using a DEVS wrapping strategy in the MECSYCO middleware," Villers-l`es-Nancy, France, 2018.

framework[80] an implementation for Eclipse papyrus as C++ API with FMI Import/Export functionality is available in the eclipse marketplace[81] [82].

Facts

- **Developers:** CEA, French Alternative Energies and Atomic Energy Commission, Pauline Deville
- **Active development:** yes, last commit 20.04.2020 https://git.eclipse.org/c/papyrus/org.eclipse.papyrus-moka.git/
- **Licence:** EPL 2.0
- **Open source:** no
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** Finite state machines, Gauss-Seidel
- **Time model:** DES, CT
- **Domain-agnostic:** yes
- **Supported standards:** FMI
- **Supported platforms:** Eclipse papyrus

Mosaik

Mosaik as a co-simulation tool written in Python which organizes the data exchange between simulators and coordinates the execution of the connected simulators. The main purpose is to simulate the complex dependencies that occur in smart grids[83]. However it is focused on providing a high usability and flexibility by using new forms of simulation approaches like the **M**ulti-**A**gent **S**ystem (MAS)[84]. The Mosaik co-simulation architecture can be divided into the core framework, the set of adapters and additionally utility software. It can be used as a master and connect FMUs[85].

Facts

- **Developers:** OFFIS
- **Active development:** yes, last commit 20.12.2019 https://bitbucket.org/mosaik/mosaik/
- **Licence:** LGPL
- **Open source:** yes
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** unknown

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[80] M. Aslan, U. Durak, H. Oguztüzün and K. Taylan, MOKA: An Object-Oriented Framework for FMI CO-Simulation, Chicago, 2015.
[81] https://ci.eclipse.org/papyrus/view/Moka/job/papyrus-moka-master/lastSuccessfulBuild/artifact/releng/org.eclipse.papyrus.moka.p2/target/repository/
[82] https://wiki.eclipse.org/Papyrus/UserGuide/ModelExecution#Update_sites
[83] „Mosaiks Documentation," [Online]. Available: https://mosaik.readthedocs.io/en/latest/index.html. [Zugriff am 12 03 2020].
[84] C. Steinbrink, M. Blank-Babazadeh, A. El-Ama, S. Holly, B. Lüers, M. Nebel-Wenner, R. P. R. Acosta, T. Raub, J. S. Schwarz, S. Stark, A. Nieße und S. Lehnhoff, «CPES Testing with MOSAIK: Co-Simulation Planning, Execution and Analysis,» MDPI, Oldenburg, Germany, 2019.
[85] «mosaik,» [Online]. Available: https://mosaik.offis.de/. [Zugriff am 12 03 2020].

- **Time model:** DES
- **Domain-agnostic:** yes
- **Supported standards:** FMI, OPC UA, MAS
- **Supported Platforms:** Linux, OSX, Windows

Microsoft Azure Digital Twin Software

Microsoft Azure Digital Twin Software is an IoT service dedicated to helping businesses create comprehensive, creative models of their physical environments. It virtually replicates the physical world by modelling the relationships between people, places and devices in a spatial intelligence graph, improving consumer experiences and the spaces in which people live, work and play[86]. It applies to various types of use cases environments, including predicting the maintenance requirements for a factory[87].

Facts

- **Developers:** Microsoft
- **Active development:** yes
- **Licence:** commercial
- **Open source:** no
- **Monolithic:** no
- **Distributable:** unknown
- **Models of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** no
- **Supported standards:** none
- **Supported platforms:** unknown

OMSimulator

The Open Modelica Simulator, abbreviated as OMSimulator, is a co-simulation environment for large-scale simulation. By using the FMI standard it can handle prototypes from different simulations disciplines like electrically, mechanically, hydraulically and software approaches[88]. It can handle soft real-time or offline simulations even in a standalone version. The composite models are constructed as a tree of building block, the connection can either be TLM based, weakly coupled or strongly coupled system.

- TLM based connections can be recognized as physical motivated delayed connections
- In weakly-coupled systems all components run independently only synchronized by a master algorithm

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[86] “Azure Digital Twins,” [Online]. Available: https://azure.microsoft.com/en-gb/services/digital-twins/. [Accessed 04 2020].

[87] https://docs.microsoft.com/de-de/azure/digital-twins/about-digital-twins

[88] L. Ochel, R. Braun, B. Thiele, A. Asghar, L. Buffoni, M. Eek, P. Fritzson, D. Fritzson, S. Horkeby, R. Hällquist, A. Kinnander, A. Palanisamy, A. Pop and M. Sjölund, “OMSimulator - Integrated FMI and TLM-based Co-simulation with Composite Model Editing and SSP,” Linköping, Sweden, 2019.

- Strongly-coupled systems wrap-up ME FMUs into a co-simulation unit with a common shared solver and usage of a continuous communication schema

OMEdit is a graphical editor by OpenModelica which has been implemented into the OMSimulator.

Facts

- **Developers :** Linköping University
- **Active development**: yes, last commit 04.2020 https://github.com/OpenModelica/OMSimulator
- **Licence:** OSMC-PL, GPL
- **Open source:** yes
- **Monolithic**: no
- **Distributable**: yes
- **Models of computation**: unknown
- **Time model:** DES
- **Domain-agnostic**: yes
- **Supported Standards**: FMI
- **Supported platforms**: Windows, Linux, Mac

Plant Simulation

Plant Simulation is a discrete event simulation software for the analysis, visualization and optimization of production processes. Within the simulation the material flow and logistic processes can be incorporated. The Plant Simulation belongs to the area of **P**roduct **Li**fecycle **M**anagement (PLM) software, which, with the help of computer simulations, makes it possible to compare complex production alternatives.

With the script programming language SimTalk, which is invented by the Siemens AG, the behaviour of models can be accurately described[89].

Bangsow presents 150 use cases to demonstrate how plant simulation and SimTalk can be used. He describes in detail how robots, workers and transport logistics can be simulated together.

Facts

- **Developers** : Siemens AG, Siemens Industry Sector
- **Active development**: yes, last commit 2019
- **Licence**: proprietary
- **Open source**: no
- **Monolithic**: no
- **Distributable**: yes
- **Models of computation**: unknown
- **Time model:** DES
- **Domain-agnostic**: yes
- **Supported standards**: none

[89] M. Eley, Simulation in der Logistik, Aschaffenburg: Springer, 2012.

- **Supported platforms**: Windows XP, Vista, 7, 8

PowerDEVS

PowerDEVS is a general purpose software tool for DEVS modelling and simulation oriented to the simulation of hybrid systems[90]. The environment allows defining atomic DEVS models in C++ language that can then be graphically coupled in hierarchical block diagrams to create more complex systems. PowerDEVS includes a model editor, atomic editor for DEVS, a pre-processor, a simulation interface and a workspace corresponding to a Scilab instance. Scilab is a numerical computational package by the "Institut National de Recherche en Informatique" under the open source licence GPL.

Facts

- **Developers** : At Universidad Nacional de Rosario (Argentina) by Ernesto Kofman, Federico Bergero, Gustavo Migoni, Enrique Hansen, Joaquín Fernandez, Marcelo Lapadula and Esteban Pagliero
- **Active development**: yes, last commit 03.05.2019 https://sourceforge.net/projects/powerdevs/
- **Licence**: AFL, GPLv2
- **Open source**: yes
- **Monolithic**: no
- **Distributable**: unknown
- **Models of computation**: Euler, Runge-Kutta
- **Time model:** DES, hybrid
- **Domain-agnostic**: yes
- **Supported standards**: DEVS
- **Supported platforms**: platform independent

Ptolemy II

The software Ptolemy II is an open source framework for modelling and simulation of cps. It originated from the Ptolemy project which focusses on the modelling, simulation and design of concurrent, real-time, embedded systems. It was developed for embedded system simulation. Due to its modularity and hierarchical modelling architecture it is capable of simulating cyber physical systems as well[91].

A Ptolemy II model consists of two components, actors and directors. Being scheduled by a director the actors gather information from input ports and transfers them to output ports.

Facts

- **Developers:** Edward A. Lee (UC Berkeley), Janette Cardoso
- **Active development:** yes, last commit 09.03.2020

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[90] F. Bergero and E. Kofman, "PowerDEVS: a tool for hybrid system modeling and real-time simulation," in *Simulation: Transactions of the Society of Modeling and Simulation International*, 2010.

[91] Z. Nie, P. Wang, P. Zeng and H. Yu, "Modeling Industry 4.0 Demonstration Production Line Using Ptolemy II," Shenyang, China, 2017.

https://github.com/icyphy/ptII
- **Licence:** BSD
- **Open source:** yes
- **Monolithic:** no[92]
- **Distributable:** unknown
- **Models of computation:** Multiple
- **Time model:** DES
- **Domain-agnostic:** no
- **Supported standards:** FMI
- **Supported platforms:** platform independent

PyFMI

PyFMI is a package that allows working with FMUs via an interface. It extends the FMI standard by providing a master code for orchestration of the co-simulation. Since the FMI standard does not bring a master code for orchestrating the co-simulation the PyFMI claims to deliver one at the latest state of art of co-simulation[93].

PyFMI is available as a stand-alone package or as part of the JModelica.org distribution. Using PyFMI together with the Python simulation package Assimulo adds industrial grade simulation capabilities of FMUs to Python. With Assimulo the solving of ordinary differential equations containing various solvers becomes possible[94].

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[92] C. Steinbrink, F. Schlögl, D. Babazadeh, S. Lehnhoff, S. Rohjans und A. Narajan, *Future Perspectives of Co-Simulation in the Smart Grid Domain,* Oldenburg, 2018.
[93] C. Winther, "Modelon," [Online]. Available: https://www.modelon.com/co-simulation-using-the-open-source-python-package-pyfmi/. [Accessed 17 04 2020].
[94] C. Andersson, "Methods and Tools for Co-Simulation of Dynamic Systems with the Functional Mock-up Interface," Lund, Sweden, 2016.

Facts

- **Developers** : Christian Winther
- **Active development**: yes, last commit 16.12.2018 https://pypi.org/project/PyFMI/
- **Licence**: GNU
- **Open source**: yes
- **Monolithic**: no
- **Distributable**: yes
- **Models of computation**: ODE
- **Time model:** DE, CT, hybrid
- **Domain-agnostic**: yes
- **Supported standards**: FMI
- **Supported platforms**: platform independent

Roboguide

Roboguide is a robot and work cell simulator developed by FANUC that provides an environment for offline robot programming to review, optimize, debug and verify robot behaviour. It provides a “plug-and-simulate” package for robots operating in work cells.

The software is packaged with standard features and optional application-specific add-ons. Standard functionality includes device modelling and layout, robot programming and simulation. Additional functionality is provided through add-ons which support, for example, chamfering, material handling, painting, palletizing, pick-and-place and welding.

Roboguide is actively developed and supported by FANUC and has a simple, intuitive design. Programmatic interaction with the simulation is achieved using the same SDKs available for interacting with physical robots. This feature allows for the simulation of input on the virtual robot to accurately reflect real-world scenarios and reduces software development time. Robot programs created or optimized with Roboguide can be extracted from the simulation and used directly on physical robots.

Without needing access to the SDK, robot data can be retrieved from Roboguide over HTTP as the virtual controller for simulated robots is available by default. This web interface exposes information regarding robot position, system variables, programs and program parameters. While Roboguide’s main purpose is offline programming, it allows for data collection, verification and analysis as a robot runs through a cycle.

Applications

Roboguide is referenced in several studies on offline robot programming, including research of sporting movements, laser remanufacturing and surface path generation. While Roboguide has found applications across a wide assortment of domains, it has shown varying levels of success.

Robot performance optimization with the use of a vision system was explored by Jamaluddin *et al.*[95] In order to use vision systems to improve robot dynamic performance, the authors argue, it is necessary first to prove accurate forward and reverse kinematics in simulation. Here, Roboguide was used to simulate positional changes using calculations from Matlab to compare positional data with a physical FANUC robot of identical model, which the authors found to be completely identical.

Jin and Yang utilized Roboguide in their research into offline robot programming for laser remanufacturing[96]. For their work, Roboguide provided graphical simulation and control program generation. Their work reflects on the benefits of offline programming including the time economy of avoiding impacts to production lines.

Robotics in the running shoe industry is finding applications in new areas, such as biofidelic mechanical testing for evaluating performance of shoes under realistic conditions, as Jones *et al.* explore in their research[97]. In this study, the viability of using Roboguide as a substitute for a physical robot is determined, using a high-speed camera for comparisons. The simulation in Roboguide does not provide feedback of contact between the end effector and force platform, but does provide collision information which can be used to determine ground contact time. One configuration for testing is shown in the following image.

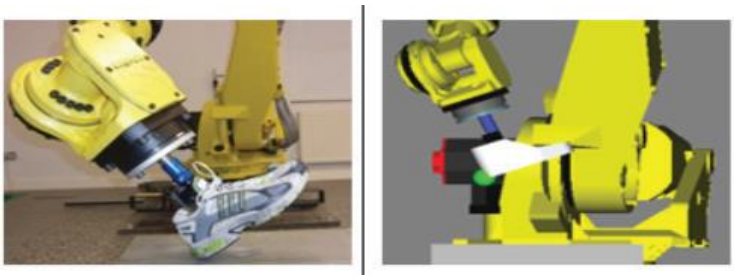

Figure 8: Comparing Roboguide with physical robot performance[98].

The study showed that Roboguide results did not closely match the physical robot results in kinematics nor contact timing for the more complex heelstrike trials. In spite of lackluster results, Roboguide is referenced as providing advantages in avoiding altering production performance while testing, reducing downtime and improving efficiency.

For path planning verification, Roboguide was found suitable by Lui, Yang and Zhang[99]. In their study, point cloud data is transformed into part models and robot paths with

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[95] Jamaluddin, M. H., Said, M. A., Sulaiman, M., & Horng, C. S. (2006, June). Vision guided manipulator for optimal dynamic performance. In 2006 4th Student Conference on Research and Development (pp. 147-151). IEEE.
[96] Jin, X., & Yang, X. (2009). Off-line programming of a robot for laser re-manufacturing. Tsinghua Science & Technology, 14, 186-191
[97] Jones, J. A., Leaney, P. G., Harland, A. R., & Forrester, S. E. (2012). Validation of RoboGuide to support the emulation of sporting movements using an industrial robot. Procedia Engineering, 34, 307-312.
[98] Ibid.
[99] Liu, L. F., Yang, X. C., & Zhang, H. M. (2012). Planning Strategies for Surface Hardening by Laser Robot. In Advanced Materials Research (Vol. 433, pp. 5775-5779). Trans Tech Publications Ltd.

Mathematica which can subsequently be tested and compared in a Roboguide simulation. Once the simulation results are found adequate, the resulting program can be exported from Roboguide to a physical robot for execution. The authors conclude that Roboguide provides good flexibility in this application.

One final application of Roboguide is from Kharidege and Yajun, who take another look at path generation.[100] For use cases including burr removal, polishing, lapping and buffing, manual operation is slow and error prone. Robotics and automation can be applied here to reduce errors and improve efficiency. These robots are generally programmed through a teach pendant, which is time consuming and skill dependent. By using a CAD model and MATLAB to generate paths, a robot can be programmed to perform a polishing task without the use of a teach pendant.

Use- / Misuse Cases

Relevant to use-and-misuse cases of Cyberfactory#1, Roboguide has applicability in a variety of scenarios. The table below provides a brief overview of the features or characteristics of Roboguide and how they may be applicable for Cyberfactory#1 use-cases.

Partner	Use Case Summary	Relevant Supporting Feature or Characteristic of Roboguide
Airbus D&S	Roboshave: Optimization of robotic manufacturing system by automation based on IIoT	• Optimize system using Fanuc robot • Precise measurement of operation time • Retrieve, save and review historical data
S21Sec	CPS-based manufacturing on auxiliary manufacturing industry (Global security policy enforcement)	• Data collection and correlation from Roboguide virtual controller • Demonstrate visibility and traceability of simulated robot • Demonstrate how cyber-security can be achieved on Fanuc robot
Bittium	Cyber secure networked suppy chain and information architecture	• Real-time visualization of manufacturing process

[100] Kharidege, A., & Yajun, Z. (2017). A practical approach for automated polishing system of free-form surface path generation based on industrial arm robot. The International Journal of Advanced Manufacturing Technology, 93(9-12), 3921-3934.

Partner	Use Case Summary	Relevant Supporting Feature or Characteristic of Roboguide
High Metal	Cheese making, IoT process lines and machinery • IIoT Enhanced process control • Cyber secure IoT solutions • Utilize new technologies (automation, robotics)	• Test and evaluate process performance using Fanuc robots
Vestel	Secure and optimized factory information and logistic management • Optimize material handling • Increase productivity • System security • Data accumulation and analysis	Some applicability for testing data collection and evaluating how 6-axis robots may be beneficial to material handling optimization/productivity.
InSystems	ProANT transport robot fleet in factories • Self-optimizing and self-organizing systems • Run-time reconfiguration • Historical data storage	• Developing techniques for reconfiguration using ML • Demonstrate real-time reconfiguration • Development of techniques for detection and prediction of anomalies

Facts[101] [102]

- **Developers**: FANUC
- **Active development**: yes, release 01.03.2020
- **Licence**: yes
- **Open source**: no
- **Monolithic**: unknown
- **Distributable**: unknown
- **Models of computation**: unknown
- **Time model:** unknown
- **Domain-agnostic**: no
- **Supported standards**: unknown
- **Supported platforms**: Windows

ROS-Simulator

ROS is a meta-operating system for robots. It provides an open platform for language-independent and network-transparent communication for a distributed robot control system. The individual parts in the network are called Nodes and each Node can be developed independently as long as it incorporates the ROS framework, which is available

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[101] "ROBOGUIDE," Fanuc, [Online]. Available: https://www.fanuc.eu/de/de/roboter/zubeh%c3%b6r/roboguide. [Accessed 27 04 2020].
[102] "FANUC Roboguide V9 rev.H," [Online]. Available: https://filecr.com/windows/fanuc-roboguide/. [Accessed 27 04 2020].

wrapped in a dedicated library for several common languages. This allows great flexibility in developing, implementing and updating Nodes after deployment.

The actual communication in ROS can happen in one of two ways. The primary mode of communication is an asynchronous publish and subscribe system, whereby Nodes can publish data onto a Topic which another Node can subscribe to. The Topic acts as a message buffer. A more direct way of attaining data is via a call and response service setup. The Nodes themselves are completely unaware of each other and only know Topics and services. The communication is overseen by a Master which also contains a server for globally available parameters. Once a Node has registered its presence with the Master, it can begin to advertise and subscribe to Topics and advertise and call services. ROS provides a list of standard massage types that can be expanded upon with custom made types to serve the needs of the individual Node.

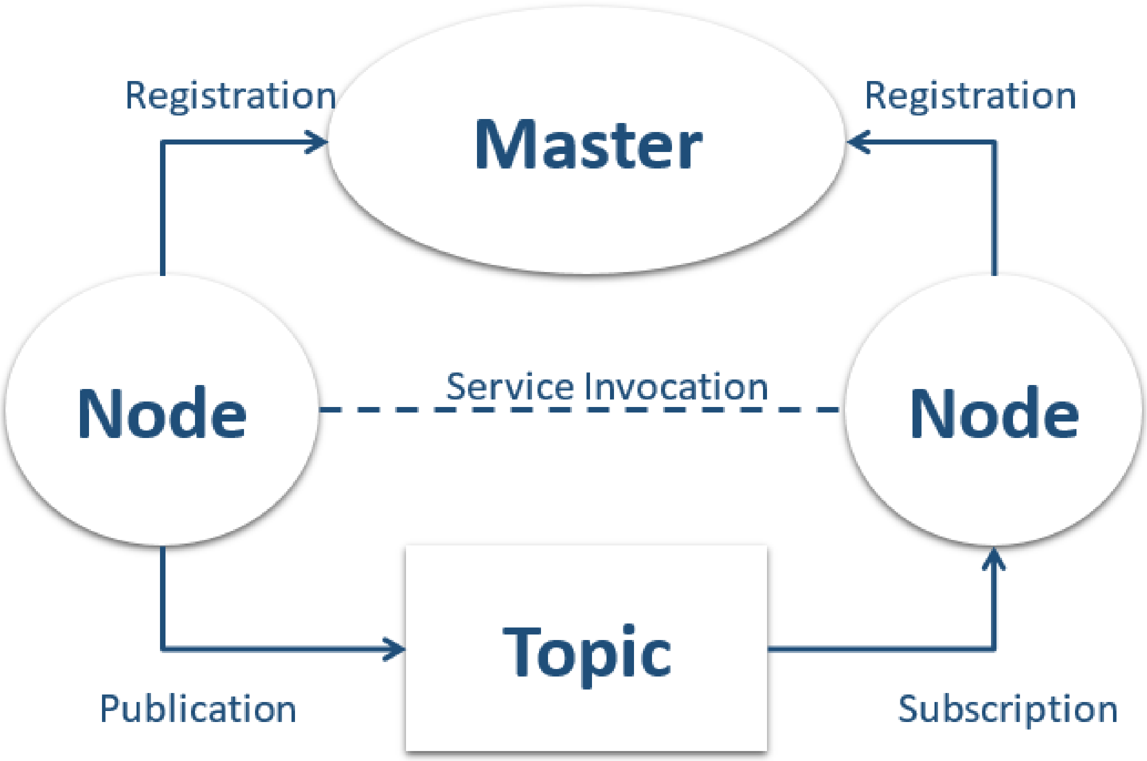

Figure 9: Basic Diagram for communication of Nodes in the ROS-Framework.

Simulation

While ROS itself is a meta-operating system, it does provide simulation tools so Nodes and updates can be tested in a safe environment before they are deployed on a real robot. While there are a number of Simulators, that can be fitted with a ROS library to use them in conjunction with a ROS robot, the two most prevalent simulators are Gazebo and Stage. InSystems is focusing on the Stage simulator since its minimalistic environment model provides better performance than Gazebo with its extensive physics engine. The setup for simulating transport robots or AGVs (Autonomous Guided Vehicle) consists of several components.

Stageros[103]

That is Stage with hooks for the ROS-Framework. It provides a simple simulated environment for the AGVs to drive around in. The robot model within stage can be equipped with a laser that provides environment feedback on a preset angel and granularity. In case of InSystems this is usually a 270° field with 1080 data points to represent the laser scanners on many of their AGVs. This simulator has the advantage, that it can support a large number of computationally cheap robot models. It also provides the ability to validate physical context. I.e. if a corridor is too narrow for an AGV to navigate or if two AGVs end up in a dead lock with each other because of the geometry of the map layout. There is rudimentary support for the adjustment of the simulation rate. To change the simulation speed, a restart of the application is required. This also applies to adding or removing of robots.

Figure 10: Visualization of a Map, transport Robots and their goals read from a mapfile in Stageros.

ROS-Stack[104] [105]

This is the logic part of the ROS-Setup as it would be running on a ROS-AGV. This stack will have to be adjusted so that it can work in a simulation without any actual robot hardware attached to it. Without the parts of the ROS-Stack that concern themselves with actual hardware communication and a simplified localization, the simulated AGV will still require a not insignificant amount of processing power for the navigation module. This can become a problem when several AGVs are to be simulated on one PC. Especially when this simulation is then run at an accelerated speed. The problem here is, that the entire ROS-Stack can require significant amounts of processing power during simulation. Several running stacks can quickly drive a PC with common hardware specs to its limits and render the simulation at accelerated speeds inoperable. Therefore there are two versions of the ROS-Stack for a simulated AGV. One stack that is as close as possible to the one running on a real AGV to simulate navigation. And one severely reduced stack, currently under development, which simulates live navigation by using a set of pre calculated paths to enable the simulation of a fleet of AGVs without overtaxing common PC hardware.

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103 "ROS.org - Documentation," 2020. [Online]. Available: https://wiki.ros.org.
104 "ROS.org - Documentation," 2020. [Online]. Available: https://wiki.ros.org.
105 "GithHub - ROS packages," 2020. [Online]. Available: https://github.com/ros/ros/tree/kinetic-devel .

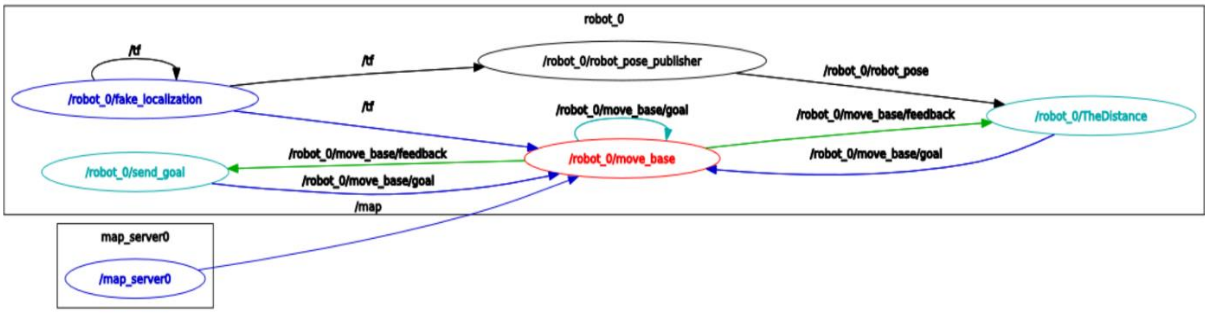

Figure 11: Diagram of Nodes for navigation and the Topics connecting them as part of the ROS-Stack of a simulated AGV.

CAC

The module which tells the AGVs where to drive and when. The role of this orchestration module can be performed by one of two InSystems software solutions. The tried and true AIC (AGV Interface Controller), which is a centralized solution where one application can control several AGVs or the decentralized CAC (Collaborative AGV Controller) which is currently under development. In the context of simulations for the FoF the orchestration is done by the CACs, where one CAC is responsible for the control of one AGV.

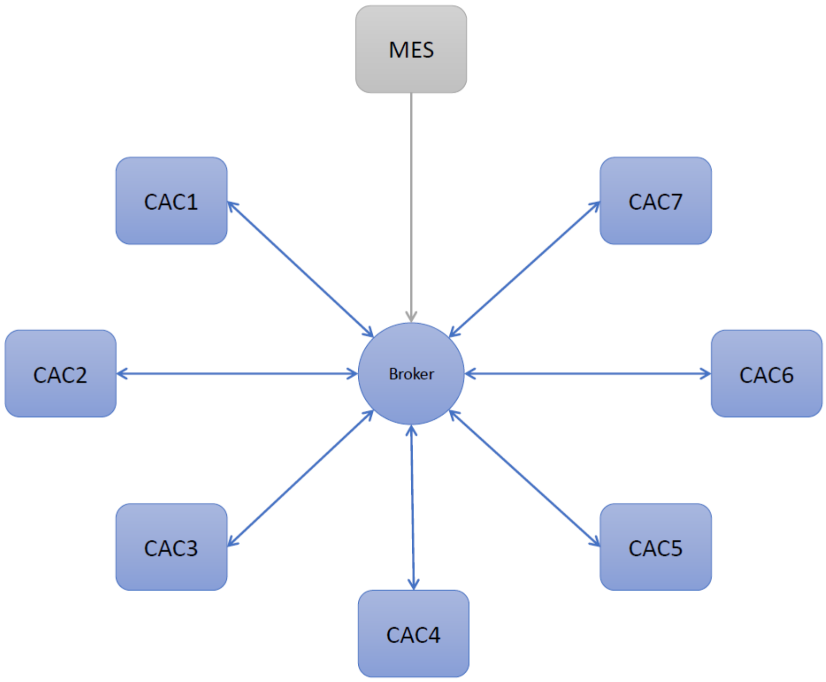

Figure 12: Diagram of a Network of CACs.

Within the CAC-Framework there is a module, which simulates a MES (Machine Execution System) that advertises transport jobs to a fleet of AGVs, that are represented by their CACs and the AGV-ROS-Stack each CAC is controlling. The CACs then start a bidding process for the transport job. The bid values are influenced by several factors which in turn may receive a different weighting, depending on the overall transport strategy that is currently in effect.

Example:

If a transport strategy like ASAP (As Soon As Possible) is in use, the distance of the AGV to the source goal of the transport is given a greater weighting than the current battery value of the AGV. If a transport strategy like W&T (Wear and Tear) is in effect, the AGVs battery value is given a greater weighting and the distance to the source goal of the transport is given a lesser weighting than for ASAP.

Once a winner for the transport job has been determined, the winning CAC will give goal instructions to the simulated AGV to head to the source goal for the transport. Once the AGV sends feedback that it reached the goal the CAC initiates the load transfer to receive the payload and then sends the AGV to its destination to unload. Whether or not load transfer is handled by the CAC and what the respective set of instructions and feedback looks like depends on the individual customer use case. Standard is a load bearing conveyor belt on the AGV.

Simulator

Put together, the three elements above constitute the ROS-Simulator which serves to test peripheral software components that can be of relevance in the FoF.

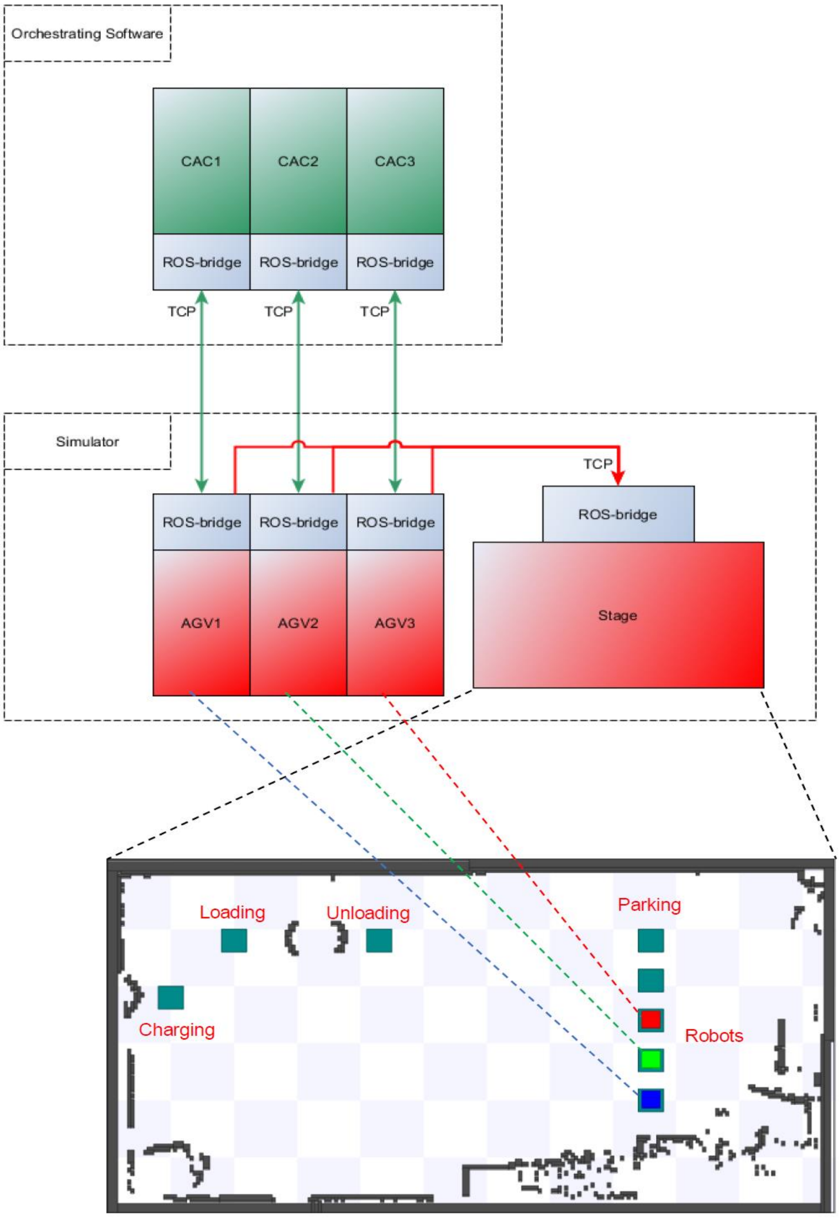

Figure 13: Diagram of the ROS-Simulator.

Facts

- **Developers:**
  ROS: Open Robotics formerly Open Source Robotics Foundation (OSRF)
  Stage (Player Stage): Richard Vaughan (OSRF)
  Stageros: William Woodall (OSRF)
- **Active development:**
  ROS: Yes
  Stage (Player Stage): No
  Stageros: No
- **Licence:**
  ROS: BSD 3-Clause "New" or "Revised" License
  Stage (Player Stage): GNU General Public License version 2
  Stageros: BSD
- **Open source:**
  ROS: Yes
  Stage (Player Stage): Yes
  Stageros: Yes
- **Monolithic:** No
- **Distributable:** Yes
- **Model of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** no
- **Supported standards:** none
- **Supported platforms:** Linux, C++, Python, Lisp, Java, Lua

Seebo Digital Twin Software[106]

Seebo Digital Twin software is a graphical interface that allows the generation of actionable insights that maximize overall equipment effectiveness (OEE), reduce unplanned downtime, and uncover the root cause of issues. By drilling through a digital twin, it is possible to pinpoint performance anomalies and their root cause. The use of dashboards allows the real-time visualization of the operational health of deployed machines, receives intelligent alerts with predictive metrics based on key machine parameters, such as machine temperature, pressure, vibration, humidity, fatigue, and wear in order to quickly identify and solve issues remotely.

Facts

- **Developers:** Seebo Interactive LTD
- **Active development:** yes
- **Licence:** yes
- **Open source:** no
- **Monolithic:** unknown
- **Distributable:** unknown

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[106] "Seebo Industrial IoT Platform," [Online]. Available: https://www.seebo.com/digital-twin-software/. [Accessed 04 2020].

- **Models of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** yes
- **Supported standards:** unknown
- **Supported platforms:** Microsoft Azure

SimPy

SimPy is a process-based discrete-event simulation framework based on standard Python.

Simulations can be performed “as fast as possible”, in real time (wall clock time) or by manually stepping through the events[107].

SimPy is a discrete-event simulation library. The behaviour of active components (like vehicles, customers or messages) is modelled with processes. All processes live in an environment. They interact with the environment and with each other via events.

Processes are described by simple Python generators. You can call them process function or process method, depending on whether it is a normal function or method of a class. During their lifetime, they create events and yield them in order to wait for them to be triggered.

When a process yields an event, the process gets suspended. SimPy resumes the process, when the event occurs (we say that the event is triggered). Multiple processes can wait for the same event. SimPy resumes them in the same order in which they yielded that event.

It should be mentioned that there are other frameworks with other underlying programming languages e. g. Simmer (R)[108], SimJulia (Julia)[109], SimSharp (C#)[110], C++Sim[111] and SIM.JS (JavaScript)[112]. These are all DE simulations with slight conceptual differences due to the abilities of the used programming language.

Facts

- **Developers:** Ontje Lünsdorf, Stefan Scherfke
- **Active development:** yes - last commit 09.09.2019
- **Licence:** MIT
- **Open source:** yes
- **Monolithic:** yes
- **Distributable:** no, single Computer
- **Models of computation:** process-based discrete-event

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[107] «Documentation for SimPy,» SimPy, [Online]. Available: https://simpy.readthedocs.io/en/latest/index.html. [Zugriff am 12 03 2020].
[108] I. Ucar, B. Smeets und A. Azcorra, «simmer: Discrete-Event Simulation for R,» Madrid, 2017.
[109] B. Lauwens, «Read the Docs,» 2017. [Online]. Available: https://readthedocs.org/projects/simjuliajl/downloads/pdf/latest/. [Zugriff am 09 04 2020].
[110] A. Beham, «Create .Net apps faster with NuGet,» [Online]. Available: https://www.nuget.org/packages/SimSharp/. [Zugriff am 09 04 2020].
[111] N. Byrne, J. Geraghty, P. Liston und P. Young, «The Potential Role Of Open Source Discrete Event Simulation Software In The Manufacturing Sector,» Dublin, 2012.
[112] N. Byrne, J. Geraghty, P. Liston und P. Young, «The Potential Role Of Open Source Discrete Event Simulation Software In The Manufacturing Sector,» Dublin, 2012.

- **Time model:** DES
- **Domain-agnostic:** yes
- **Supported standards:** none
- **Supported platforms:** Linux, Windows Vista

Simul8

Simul8 is a simulation software for discrete event simulation and process simulation. It allows the user to visualize the analysed model. Simul8s core engine consists of 6 part for modelling: Work, Item, Work Entry Point, Storage Bin, Work Centre, Work Exit Point, and Resource[113].

1. Work Item: This is a dynamic object (customer, product, entities) which can be described by label images (attributes) and advanced properties
2. Work Entry Point: This is an object that generates the Work Items into the simulation model according to the distribution of the inter-arrival times
3. Storage Bin: Is used to buffer the Work Items in a queue till next processes
4. Work Centre: This is the main object where activities are described, e. g. time length, resources, attributes and rulesets for previous / following movement of entities. Information’s can be gathered according to historical observed data.
5. Work Exit Point: This object describes the end of the modelled systems when all Work Items have finished their movement through the model
6. Resource: With this object the capacities of the workers, material or means of production that are used during the activities are modelled. This way limitations can be considered.

In an analysis of an automotive final assembly line the framework helped to discover bottlenecks and weak point in the production line, leading to an easier decision-making. This led to a combining of two separate processes into one and relocating the workers to another department with more need[114].

[113] J. Fousek, M. Kuncova and J. Fábry, “Discrete Event Simulation - Production Model in Simul8,” Prague, Czech Republic, 2017.
[114] J. Baraka, A. Naicker and R. Singh, “DISCRETE EVENT SIMULATION MODELING TO IMPROVE PRODUCTIVITY ON AN AUTOMOTIVE PRODUCTION LINE,” Cape Town, South Africa, 2012.

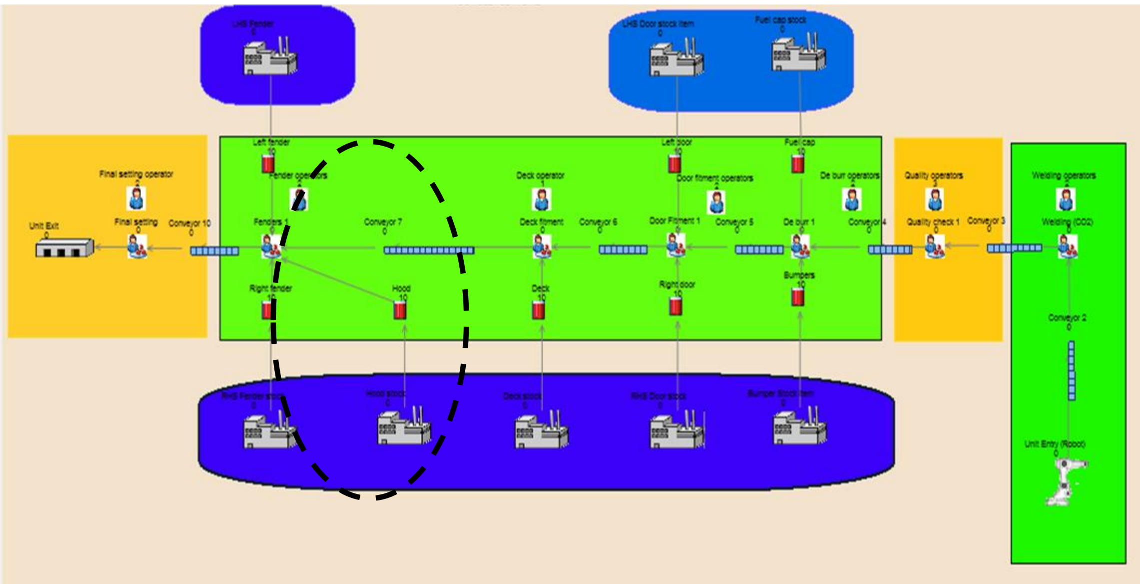

Figure 14: Combining of two processes[115].

Facts

- **Developers**: Simul8 Corporation (USA)
- **Active development**: yes
- **Licence**: proprietary
- **Open source**: no
- **Monolithic**: no
- **Distributable**: yes
- **Models of computation**: unknown
- **Time model**: DES and process based simulation
- **Domain-agnostic**: yes
- **Supported standards**: none
- **Supported platforms**: Windows NT, 95,98, 2000, XP, Vista, 7,8, 10

Webots

Webots is a development environment used to model, program and simulate mobile robots developed by Cyberbotics Ltd. The license used to be proprietary. It is particularly dedicated to mobile and multi-legged robots. It provides a unified environment, good API and frequent software updates.

Facts

- **Developers:** Cyberbotics Ltd.
- **Active development:** yes, last commit 20.04.2020 https://github.com/cyberbotics/webots
- **Licence:** Apache
- **Open source:** yes

[115] J. Baraka, A. Naicker and R. Singh, "DISCRETE EVENT SIMULATION MODELING TO IMPROVE PRODUCTIVITY ON AN AUTOMOTIVE PRODUCTION LINE," Cape Town, South Africa, 2012.

- **Monolithic:** yes
- **Distributable:** yes
- **Models of computation:** ODE
- **Time model:** unknown
- **Domain-agnostic:** no
- **Supported standards:** none
- **Supported platforms:** Linux

Wrld3d[116]

Wrld3d is an open source platform that allows the creation of digital twins in a quickly and easily manner, using a comprehensive set of self-serve tools, SDKs, APIs, and location intelligent services. As a dynamic 3D mapping platform it makes possible to create virtual indoor and outdoor environments upon which data from sensors, systems, mobile devices, and location services can be visualized within millimetre accuracy.

Facts

- **Developers:** WRLD
- **Active development:** yes
- **Licence:** yes
- **Open source:** yes
- **Monolithic:** no
- **Distributable:** yes
- **Models of computation:** unknown
- **Time model:** unknown
- **Domain-agnostic:** yes
- **Supported standards:** yes
- **Supported platforms:** Linux, Android, IOS

2.2.4. Overview of Research Results Regarding Simulation-Frameworks

In this section research papers regarding co-simulation and their impact for the FoF are introduced. They provide rather conceptual content than existing standards or marked ready tools.

A Modular Technique for Automotive System Simulation

Publication Name	A Modular Technique for Automotive System Simulation
Authors	Felix Günther, Georg Mallebrein, Heinz Ulbrich
Publication Date	2012
Reference	https://www.ep.liu.se/ecp/076/060/ecp12076060.pdf

[116] "wrld3d," [Online]. Available: https://www.wrld3d.com/. [Accessed 04 2020].

Abstract	This paper presents a modular approach consisting of two parts to handle complexity and increase the perfor-mance: a modular library for the different domains and a co-simulation framework. To begin with, coupling aspects such as causality and communication are discussed in this context and their implementation is shown. A further focus is the variable macro step size that we developed within the framework for the automotive drive cycle simulation. The results of the modular approach are described and analyzed regarding error and performance aspects. Finally, challenges of the work are mentioned and an out-look, including FMI, is given[117].
Project	none
FoF relevance	This paper shows how to realize the co-simulation for a complex system with several submodels witch is relevant for the hierachical FoF and its (probalbe also hierachical) components. Addionally it provides an comparison of parralell & and sequential simulator syncronisation.
Related WP	WP3, WP4, WP5

ADAS Virtual Prototyping using Modelica and Unity Co-simulation via OpenMETA

Publication Name	ADAS Virtual Prototyping using Modelica and Unity Co-simulation via OpenMETA
Authors	Masahiro Yamaura, Nikos Arechiga, Shinichi Shiraishi, Scott Eisele, Joseph Hite, Sandeep Neema, Jason Scott, Theodore Bapty
Publication Date	2016
Reference	https://www.ep.liu.se/ecp/124/006/ecp16124006.pdf
Summary	In this paper, a closed-loop simulation framework is proposed. The proposed simulation framework consists of four tools: Dymola, Simulink, OpenMETA and Unity 3D game engine. Dymola simulates vehicle dynamics models written in Modelica. Simulink is used for vehicle control software modeling. OpenMETA provides horizontal integration between design tools. OpenMETA also has the capability to improve design efficiency through the use of PET (Parametric Exploration Tool) and DSE (Design Space Exploration) tools. Unity provides the key functionality to enable interactive, or closed-loop ADAS simulation, which contains sensor models, road environment models and provides visualization[118].
Project	none

[117] F. Günther, G. Mallebrein and H. Ulbrich, A Modular Technique for Automotive System Simulation, Munich, 2012.
[118] M. Yamaura, N. Arechiga, S. Shiraishi, S. Eisele, J. Hite, S. Neema, J. Scott and T. Bapty, ADAS Virtual Prototyping using Modelica and Unity Co-simulation via OpenMETA, Tokyo, 2016.

FoF relevance	The authors give an example on how to structure different models and tools. The tool infrastructure OpenMETA is used to combine models for physical behavior and controling software. The environment representation by the unity model also includes human interfaces which can be suitable for employee interaction in factories.
Related WP	WP3, WP4, WP5

Co-simulation with OPC UA

Publication Name	Co-simulation with OPC UA
Authors	Stephan Hensel, Markus Graube, Leon Urbas, Till Heinzerling, Mathias Oppelt
Publication Date	2017
Reference	https://ieeexplore.ieee.org/abstract/document/7819127
Summary	This paper presents an approach to couple domain specific simulators to a co-simulation. SIMIT and FMI instances are used. SIMIT is a simulation software that is used as a complete plant simulator or as an input and output simulator of test signals for controls. Its main focus lies on the test and the virtual commissioning of automation software and operator training[119]. The OPC UA model is used as middleware technology to create a co-simulation environment that allows the further integration of models.
Project	none
FoF relevance	In the FoF is lot of automation software which needs to be modelled and simulated. This approachs seems quite interesting but still needs more research for a practical usage.
Related WP	WP3, WP4, WP5

FERAL — Framework for simulator coupling on requirements and architecture level

Publication Name	FERAL – Framework for simulator coupling on requirements and architecture level
Authors	Thomas Kuhn, Thomas Forster, Tobias Braun, Reinhard Gotzhein
Publication Date	2013
Reference	https://ieeexplore.ieee.org/document/6670936

[119] S. Hensel, M. Graube und L. Urbas, «Co-Simulation with OPC UA,» IEEE, Dresden, 2016.

Summary	FERAL is an framework for simulator coupling which enables the integration of simulators with heterogeneous simulation models. It supports the coupling of specialized simulators in offline scenarios without connecting the simulated system to real hardware to enable the creation of holistic simulation scenarios. Similar to the Ptolemy framework, FERAL distinguishes between simulators, which are integrated as simulation components, and execution models, which are integrated as directors[120].
Project	A ongoing Fraunhofer IESE project
FoF relevance	The authors claim that a specilty of FERAL is its high reuseability which simplifies the integration of simulators.
Related WP	WP3, WP4

Functional Digital Mock-up and the Functional Mock-up Interface – Two Complementary Approaches for a Comprehensive Investigation of Heterogeneous Systems

Publication Name	Functional Digital Mock-up and the Functional Mock-up Interface – Two Complementary Approaches for a Comprehensive Investigation of Heterogeneous Systems
Authors	Olaf Enge-Rosenblatt, Christoph Clauß, André Schneider, Peter Schneider
Publication Date	2011
Reference	http://publica.fraunhofer.de/dokumente/N-163024.html
Summary	In this paper the authors represant three proposals to combine the Functional Digital Mock-up (FDMU) and the Functional Mock-up Interface (FMI) to create a powerful framework for handling a broad variety of simulation tasks. Whereas the FDMU is a framework developed by four German Fraunhofer institutes the FMI is developed by a europe wide network within the MODELISAR project[121].
Project	A Fraunhofer project
FoF relevance	If the FMI is used in the FoF the FDMU should be considered to overcome disadvantages of the FMI technic.
Related WP	WP3

[120] T. Kuhn, T. Forster, T. Braun und R. Gotzheim, «FERAL - Framework for Simulator Coupling on Requirements and Architecture Level,» Portland, USA, 2013.
[121] O. Enge-Rosenblatt, C. Clauß, A. Schneider und P. Schneider, «Functional Digital Mock-up and the Functional Mock-up Interface – Two Complementary Approaches for a Comprehensive Investigation of Heterogeneous Systems,» Dresden, 2011.

Hybrid Simulation Using SAHISim Framework

Publication Name	Hybrid Simulation Using SAHISim Framework
Authors	Muhammad Usman Awais, Wolfgang Gawlik, Gregor De-Cilia, Peter Palensky
Publication Date	2015
Reference	https://eudl.eu/doi/10.4108/eai.24-8-2015.2260869
Summary	Hybrid systems such as Cyber Physical Systems (CPS) are becoming more important with time. Apart from CPS there are many hybrid systems in nature. To perform a simulation based analysis of a hybrid system, a simulation framework is presented, named SAHISim. It is based on the most popular simulation interoperability standards, i.e. High Level Architecture (HLA) and Functional Mock-up Interface (FMI). Being a distribted architecture it is able to execute on cluster, cloud and other distributed topologies. Moreover, as it is based on standards so it allows many different simulation packages to interoperate, making it a flexible and robust solution for simulation based analysis. The underlying algorithm which enables the synchronization of different simulation components is discussed in detail. A test example is presented, whose results are compared to a monolithic simulation of the same model for verification of results.
Project	none
FoF relevance	The research combines the standards HLA and FMI. In cases where HLA is needed this approach simplifies to set up the simulation. If HLA is not of further interest for the FoF it shows how FMI can be implemented in other systems to improve the performance.
Related WP	WP3, WP4

HybridSim: A Modeling and Co-simulation Toolchain for Cyber-Physical Systems

Publication Name	HybridSim: A Modeling and Co-simulation Toolchain for Cyber-Physical Systems
Authors	Baobing Wang, John S. Baras
Publication Date	2013
Reference	https://ieeexplore.ieee.org/document/6690491
Summary	Cyber-physical systems (CPS) involve communication networks, computation algorithms, control systems and physical systems. Many CPS, such as Smart Buildings, are subject to very expensive deployment costs and complex network interactions. Thus comprehensive modeling and simulation of such systems are crucial to ensure that they function as intended before deployment. Given the multi-domain nature of CPS, it is

	more appropriate to use a heterogeneous simulation environment to study system dynamics. In this paper, we design and implement an integrated modeling and co-simulation toolchain, called HybridSim, for the design and simulation of CPS. Firstly, HybridSim can transform and import existing system components from multi-domains into SysML, which enables systems engineers to design CPS with only these imported SysML blocks. Secondly, HybridSim can generate Functional Mock-up Units (FMUs) and configuration scripts directly from SysML designs. Finally, HybridSim can co-simulate these FMUs according to the Functional Mock-up Interface standard to synchronize their corresponding simulators and exchange information between them. We demonstrate the convenience and efficiency of HybridSim using a comprehensive hydronic heating system model for Smart Buildings as the case study to investigate the impact of packet loss and sampling rate introduced by the communication network.
Project	CNS-1035655 of National Science Foundaten and 70NANB11H148 of National Institute of Standards and Technology
FoF relevance	The authors designed a uniform framework which is based upon the FMI standard. Moreover the claim the possibility the integration of the NS-3 Simulator into HybridSim to achieve more features.
Related WP	WP3, WP4

Model-Based Integration Platform for FMI Co-simulation and Heterogeneous Simulations of Cyber-Physical Systems

Publication Name	Model-Based Integration Platform for FMI Co-simulation and Heterogeneous Simulations of Cyber-Physical Systems
Authors	Himanshu Neema, Zsolt Lattmann, Janos Sztipanovits, Gabor Karsai
Publication Date	2014
Reference	https://www.researchgate.net/publication/269127653_Model-Based_Integration_Platform_for_FMI_Co-Simulation_and_Heterogeneous_Simulations_of_Cyber-Physical_Systems
Summary	In this work the authors concerns about different frequencies in multi model simulations. Electrical components tend to have high frequencies than mechanical model do. A co-simulation with FMI cannot handle this so they integrate HLA as master to overcome the disadvantages. The occuring challenges are addressed and solutions are proposed with the goal to add the technic to the Command and Control Wind Tunnel (C2WT). C2WT is a model-based multi multi-model integration platform that has been developed by the authors. As outcome of the work they managed to wrap FMUs automatically as HLA-federates and execute them in the C2WT platform.

Project	US DoD „Adaptive Vehicle Make“
FoF relevance	The authors claim that their results can be used to enable the developement of System-of-System (SoS) simulations.
Related WP	WP3

Parallel Co-simulation for Mechatronic Systems

Publication Name	Parallel Co-simulation for Mechatronic Systems
Authors	Markus Friedrich
Publication Date	2011
Reference	https://mediatum.ub.tum.de/doc/1063436/856010.pdf
Abstract	This work deals with coupled simulation of multi domains, especially mechanical, hydraulic and electric ones, using co-simulation: the subsystems are integrated by their own integrators and are dynamically connected at discrete macro time steps. The main aspect lies on stability improvements and parallelization to achieve time efficient simulations on multi CPU computers. Beside analytical considerations also examples of industrial relevance are given showing the power of parallel multi domain co-simulations.
Project	none
FoF relevance	The work shows the benefits of running co-simulations on CPU clusters. The so called parallel co-simulation remains an interesting aspects to observe when the computing time of the master simulation extends expected time slots.
Related WP	WP3, WP4, WP5

RoboNetSim: An Integrated Framework for Multi-robot and Network Simulation

Publication Name	RoboNetSim: An Integrated Framework for Multi-robot and Network Simulation
Authors	Michal Kudelski, Luca M. Gambardella, Gianni A. Di Caro
Publication Date	2012
Reference	https://www.researchgate.net/profile/Gianni_Di_Caro/publication/257343897_RoboNetSim_An_integrated_framework_for_multi-robot_and_network_simulation/links/5af6c684aca2720af9c74227/RoboNetSim-An-integrated-framework-for-multi-robot-and-network-simulation.pdf

Abstract	In networked multi-robot systems, communication plays a major role defining system's dynamics and performance. Unfortunately, existing multi-robot simulators do not provide advanced communication models. Therefore, given the intrinsic unreliability of wireless communications, significant differences might be observed between simulation and real-world results. Addressing these issues, we present RoboNetSim, an integrated simulation framework for communication-realistic simulation ofnetworked multi-robot systems. RoboNetSim's integrates multi-robot simulators with network simulators. We present two modelimplementations based on ARGoS at the robotic side, and NS-2 and NS-3 as network simulators. We evaluate the framework interms of accuracy and computational performance, showing that it can efficiently simulate systems consisting of hundreds of robots. Using the Stage simulator as an example, we also show the integration of a robotic simulator with RoboNetSim by only adaptingrobot controllers, without the need to adapt the general code of the simulator. Finally, we demonstrate the effects of communication on mobile multi-robot systems. We consider two different case studies: adistributed coordination and task assignment scenario, and a coordinated mobility scenario. We compare realistic network simulation with simplified communication models and algorithms, and we study the resulting behavior and performance of the multi-robotsystem and the impact of different parameters.[122]
Project	none
FoF relevance	This work focus on the simulation a multi-robot system with their network comunication. Industrial robots and robot fleets communication via network are part of the Cyberfactory#1 use-Cases. Therefore a multi-robot network simulation framework is important for optimization and resiliance in the Cyberfactory#1 project
Related WP	WP3, WP4, WP5

VLE Framework – DEVS Coupling of Spatial and Ordinary Differential Equations

Publication Name	DEVS Coupling of Spatial and Ordinary Differential Equations: VLE Framework
Authors	Gauthier Quesnel, Raphaël Duboz, David Versmisse, Éric Ramat
Publication Date	2005

[122] M. Kudelski, L. M. Gambardella and A. D. C. Gianni, *RoboNetSim: An Integrated Framework for Multi-robot and Network Simulation,* 2012.

Reference	http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.302.5658&rep=rep1&type=pdf
Summary	In this paper the authers compare two methods for managing heterogenous models regarding Descrete Event System Specifaction DEVS standard. The focus is on adding new models to an existing simulator based on DEVS. The two methods “wrapping” and “mapping” are illustrated by ordinary differential and spatial differential equations systems. This illustration also includes the formal specifation of modles, descriptions of algorithms, a list of necessary wrapping or mapping steps and a research regarding a hybrid timing approach[123].
Project	none
FoF relevance	This paper is suitable if the DEVS standard is used for FoF simulation and should extendable with more units. Since discrete event as well as continous systems are also possible, VLE can be a appretiate framework for the FoF context.
Related WP	WP3, WP4, WP5

2.3. Summary

In this section the current state of the art regarding modelling and simulation of CPS and digital twins in factory environments is summarized. Furthermore the limitations of existing solutions and the impact on further research and development are discussed.

2.3.1. Summary of Frameworks & Tools

In this chapter, we have presented existing frameworks for digital twins in factory environments and the research carried out on this subject. Co-simulation is one tool to combine several separated digital twins to a larger digital twin. It turned out that the FMI and HLA standards for co-simulation are widely used. This shows that there is a trend to improve the interoperability of simulation tools. This benefits the co-simulation idea. Furthermore we are confronted with the question which representations of time are suitable for co-simulation.

According to Gordon[124] simulation models can be differentiated into continuous and discrete event simulations. In more recent research they are often combined in terms of a hybrid simulation. The questions remains which time model is appropriate for the FoF. For a FoF simulation the discrete event based simulation seems to best reflect the actual, fluctuating conditions. The description of operational processes in the event-based context of the FoF is virtually impossible to realize properly with differential equations without extensive computer support.

[123] G. Quesnel, R. Buboz, D. Versmisse and É. Ramat, DEVS Coupling of Spatial and Ordinary Differential Equations: VLE Framework, 2005.
[124] G. Gordon, System Simulation, Englewood Cliffs: Prentice Hall, 1969.

Another important criterion is the possibility to split the simulation over several CPU. This is mainly needed for two reasons:

1. A co-simulation consists of more than one component so it is expected to require considerable processor power.
2. A Digital Twin as the live representation of reality shall not lag behind the actual processes in the factory, especially if it is used for control purposes.

While specialized software is needed for each discrete simulation, the co-simulation itself needs to be domain agnostic. If it can only be used for a specialized purpose, as for example was previously the case with HLA, it will not be able to meet the needs of the FoF which is not restricted towards a certain industrial sector.

Some tools are specialist at simulating a certain matter, for instance CyberRange is a specialist for simulating cyber-attacks. In this context it can be a participant of co-simulation and help studying the resilience. The question remains with which co-simulation tool and standard like HLA or FMI such specialized tools can be implemented to build up a digital twin of the FoF.

If an equivalent open source solution is available, it is preferred to a product with a commercial license. Dymola, simul8 and FlexSim are co-simulation tools with DE simulation time model, however they are very costly. The open source idea is a great alternative yet needs an actively contributing community.

Co-simulation frameworks

Keeping the criteria in mind, there are a few listings that look promising, like COSSIM (HLA), MasterSim (FMI), MECSYCO (MAS, FMI, DEVS), OMSimulator (FMI) and PyFMI (FMI).

Robotic simulation frameworks

Since the robot simulation is of special interest in the scope of the project, specialized simulation software is introduced. The three most up-to-date and featured robotic simulators for a 3D environments are Gazebo, Webots and CoppeliaSim, which provide functionality for modelling and simulation the robot aspect in FoF.

2.3.2. Impact & Challenges Regarding the DT for the FoF

As described in chapter 2.1.1 the DT is a suitable concept for CPS modelling and simulation in the FoF. With DTs the virtual and physical world is linked together by mirroring the physical entities. Thereby the distributable as well as the hierarchical character of the FoF is representable by DTs because of exchangeability, combinability and domain independency.

Even if the DT is not a complete new concept, it is still more a research topic than industrial practice[125] [126]. There is no clear definition of a DT, however in the scope of the FoF we understand the DT as a live representation of physical entities which can be used for predictive simulation and control purposes. Therefor many design approaches for DT architecture, application & technologies and impact potential description exist.

To realize the simulation capability of DTs, co-simulation is a highly useful tool for DT building. To keep the expert knowledge of unit developers from several domains and bring them together, it is possible to build an overall simulation system using industrial standards like FMI & FMU. Even if the FMI standard is applicable in different use cases and wraps individual simulation units, engineers have to develop their own orchestration code. Such a master code is included by the HLA standard. Remark that a HLA simulation is time-consuming and therefore cost intestine due its big overhead and complex setup[127]. In context of our project the FMI seem to be as a good opportunity to advance regarding DT simulation and data modelling aspects.

As remarked in chapter 2.1.1 the DT mirrors the physical counterpart as a live representation. Hence the data has to be updated frequently. For co-simulation there is no requirement to keep the information in each unit about the real entity always up to date. Co-simulation without a link to the physical world at simulation time is possible even if the data and status of simulation unit is changing. The DT designer has to ensure that simulation units are feed with data frequently if he build a DT with co-simulation.

To the best of the authors' knowledge, there do not yet exist digital twin frameworks that address different aspects of the mirrored system like safety, security, optimization and resilience simultaneously. Existing frameworks for digital twins are mostly used for monitoring its real life twin, e.g. for using the observations for predicting maintenance needs. Additionally, existing digital twin frameworks do not provide the means to easily combine multiple DTs. More insights in the state of the art on modelling and simulation of factories consisting of multiple subsystems is given in Chapter 0.

3. Factory Ecosystem Modelling

During the ongoing internet era, the industrial processes all over the world have been under a huge transformation process from old to modern operation format. Industrial processes today are commonly based on the distributed manufacturing networks. These networks can be understood as ecosystems, where a set of global companies make everyday business complementing each other. This kind of collaboration needs good communication methods

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[125] H.-J. Köhler, "Digital Twin - Mirror Image with Potential," [Online]. Available: https://www.t-systems.com/en/best-practice/03-2018/focus/ethical-issues/use-cases/digital-twin-840488. [Accessed 23 04 2020].

[126] "Digital twins – rise of the digital twin in Industrial IoT and Industry 4.0," [Online]. Available: https://www.i-scoop.eu/internet-of-things-guide/industrial-internet-things-iiot-saving-costs-innovation/digital-twins/. [Accessed 23 04 2020].

[127] S. Straßburger, "Overview about the High Level Architecture for Modelling and Simulation and Recent Developments," Magdeburg, Germany, 2006.

where the internet plays crucial role. The internet based communication has created many kind of challenges and problems to be solved.

One of the business related problem is the transaction costs, which have increased due to the distributed manufacturing processes. Different kinds of coordination, management and communication activities are needed to run the business. The second challenge concerns security issues. The massively increasing communication through the internet, e.g. via IoT devices, has created a lot of new risks for the business. Business stakeholders need to understand these issues and find solutions to the challenges to successfully run their business in the future.

This chapter compiles the current knowledge on business ecosystem modelling approaches. First, several approaches to model the stakeholder relationships within the business ecosystems are presented. After that some tools to model these business relationships and processes are introduced. Finally, approaches to model the cyber risks in business ecosystems and especially supply chains are presented.

3.1. Modelling approaches

3.1.1. Ecosystem Modelling Approaches

6C framework for business ecosystems

Rong et al.[128] have made an extensive study on business ecosystem theories and approaches in the context of applying IoT systems and how these new technologies should be considered from business ecosystem theory perspective. Their work provides a timely framework for CyberFactory#1 ecosystem modelling considerations as well. Following is a short description of the main elements of the 6C framework Rong at al. have developed.

1. Context
    - The context dimension aims to identify the environmental features of a supply network, such as the driving forces, main barriers and key missions from the perspectives of complexity and dynamism. It mainly answers questions such as why a certain type of supply network emerges.
2. Cooperation
    - Cooperation reflects the mechanisms by which partners interact (collaboration mechanism and governance system) in order to achieve the common strategic objectives. Instead of traditional arms-length supplier-customer relationship, cooperation emphasises the dependence of the parties and demonstrates the linkage between the constructive elements and the ecosystem configuration. The cooperation process will varies along the lifecycle (e.g. context) of a business ecosystem.

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[128] Rong Ke, Hu Guangyu, Lin Yong, Shi Yongjiang, Guo Liang (2015).Understanding Business Ecosystem Using a 6C Framework in Internet-of-Things-Based Sectors. Int. J. Production Economics, Volume 159, January 2015, Pages 41-55

3. Construct

   - The construct dimension defines the fundamental structure and supportive infrastructure of a business ecosystem. Rong et al. build this dimension on the structure-infrastructure model introduced by Hayes and Wheelwright[129]. Rong et al. suggest it had a significant impact on system-manufacturing strategy and have been adopted to studies in different levels of analysis, e.g. intra-firm level, inter-firm supply-chain level, global-engineering network level, and global-supply network level.

4. Configuration

   - Configuration dimension identifies the external relationships among partners in the business ecosystem and its configuration patterns. The way the constructive elements and processes of each system are integrated delivers various configuration patterns, which demonstrate the typical manufacturing strategy. Process and product elements were first used to categorize different patterns of manufacturing system, such as project-based, job-flow, batch, line-flow and machine-paced flow[130]. Since then, according to Rong et al., the configuration-pattern concept has been developed and extended to network level (with geographic dispersion and manufacturing coordination) and more recently adopted as an essential dimension in the study of global engineering networks, supply networks, and modular supply networks.

5. Capability

   - The capability dimension investigates the key success features of a supply network from the functional view of design, production, inbound logistics and information management[131]. It aims to answer questions such as why one type of modular supply network operates better than another. The capability perspective proposes that instead of responding reactively to the new industrial environment, it is more important for firms to focus on their capabilities. Since a configuration has a particular structure and operational mechanisms, it also has its own unique capabilities to achieve strategic requirements. The capabilities of communication and sharing, integration and synergizing, innovation and learning, and adaptation and restructuring have been identified as capability categories in global supply-network levels[132].

6. Change

   - Change in the business ecosystem demonstrates how a system configuration pattern shift dramatically from one type to another[131]. The Global Manufacturing

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[129] Hayes,R.H.,Wheelwright,S.C.,1984.Restoringour Competitive Edge:Competing Through Manufacturing. John Wiley & Sons Inc, New York.
[130] Ibid.
[131] Rong Ke, Hu Guangyu, Lin Yong, Shi Yongjiang, Guo Liang (2015).Understanding Business Ecosystem Using a 6C Framework in Internet-of-Things-Based Sectors. Int. J. Production Economics, Volume 159, January 2015, Pages 41-55
[132] Srai, J.S, Gregory, M.,2008.A supply network configuration perspective on international supply chain development. Int. J. Oper. Prod. Manag. 28, 386–411.

Virtual Network (GMVN), international strategic alliance as well as virtual organizations are examples of the pattern shifting of manufacturing systems[133]. The system pattern shifting indicates specifically systems′ configuration and cooperation evolution which indicates the renewal of the general way that key firms interacted with their business environment as well as with core business partners[131]. The change dimension demonstrates how the configuration pattern of a business ecosystem is renewed.

Rong et al. have concluded that one avenue for further research could be to study in more detail business ecosystem cooperation instead of firm-level operation. They call for more detailed investigation to business ecosystem operational mechanisms, i.e. how different firms interact during each lifecycle phase.

From the CyberFactory#1 ecosystem modelling perspective the four dimensions of 6C, namely, cooperation, construct, configuration and capability seem to be the most relevant. The change dimension is depicted in the project idea itself, where factories of future are seen becoming more automated and more connected.

Service-based industry ecosystem modelling

Peter & Gricas[134] have developed an modelling approach pertaining to 6C ecosystem framework. They have divided the modelling to three different methods: actor-relation modelling, data-relation modelling and service based datarelation modelling. These are descibed in the following sub-chapters.

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[133] Shi, Y.J.,Gregory, M., 2001.Global Manufacturing Virtual Network (GMVN): A new Manufacturing System for Market Agility and Global Mobility.
[134] Peter, Marco and Grivas, Stella Gatziu (2017) An Approach to Model Industry Ecosystems - Enabling an Ecosystem for Service Platforms. Published in ICServ17 – The 5th International Conference on Serviceology.

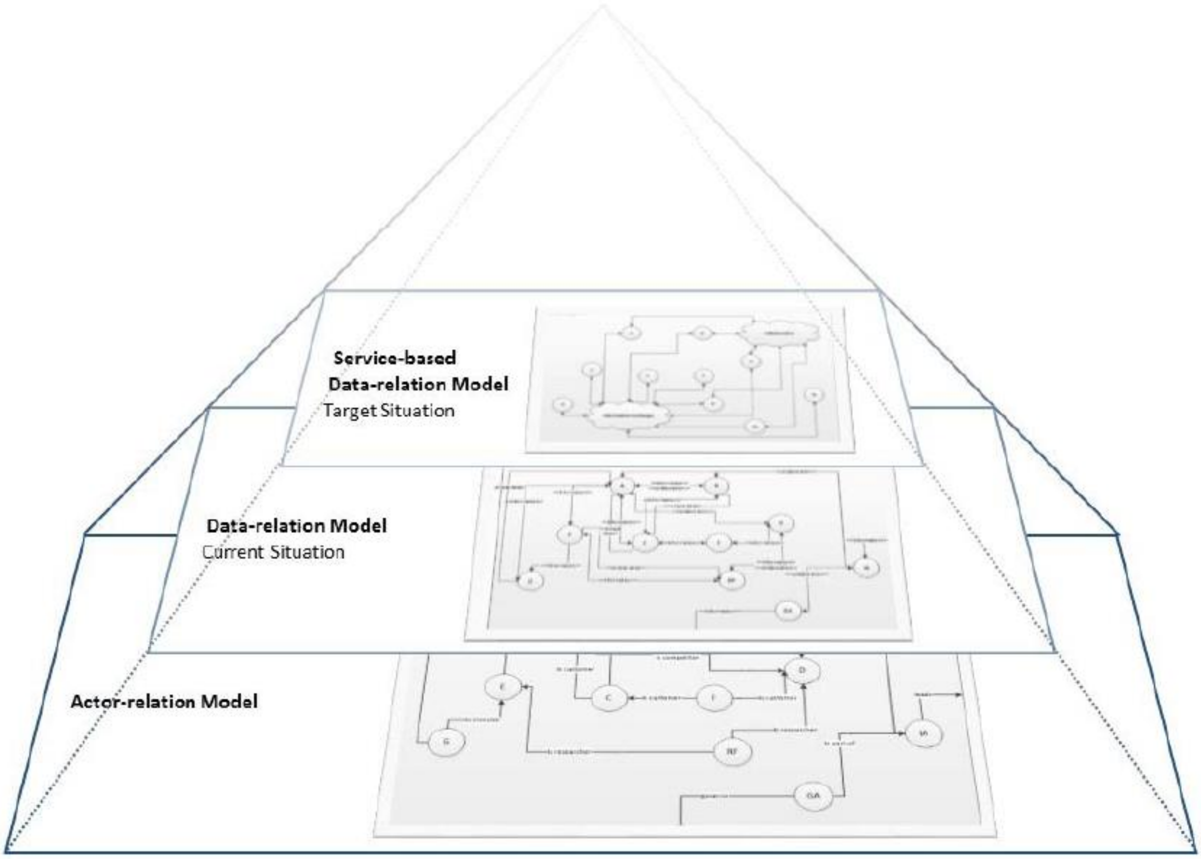

Figure 15: An Approach to Model Industry Ecosystems - Enabling an Ecosystem for Service Platforms [135].

Actor-relation modelling method

In order to know all the actors within an industry ecosystem, an overview of the current situation should be developed. Peter & Grivas suggest that the best way to do so is by first collecting all the different actors involved in the industry ecosystem. Second, the connections between those actors need to be documented and included into the design. The combination of these two steps results in an actor-relation modelling method[135].

Reflecting the 6C framework, Peter & Grivas suggest that the actor-relation modelling method supports the context and cooperation components of the 6C framework. The model provides insights on the environment of the industry ecosystem such as all the involved actors and the type of relation between them. Also, the developed model can illustrate the context component of non-direct business partners like government agencies[135].

Data-relation modelling method

After knowing which actors are involved within the industry ecosystem and how their relations are, the type of data exchange between the actors needs to be specified. Peter & Grivas (2017) suggest the following types: simple data exchange, information exchange,

[135] Peter, Marco and Grivas, Stella Gatziu (2017) An Approach to Model Industry Ecosystems - Enabling an Ecosystem for Service Platforms. Published in ICServ17 – The 5th International Conference on Serviceology.

and collaborative data ex-change. There can be none, one, two, or even three connections between the actors.

From content perspective, Peter & Grivas[136] identify five levels: data, information, knowledge, understanding, and wisdom. Data is raw content like symbols while information is processed data that results in meaningful data. The levels from knowledge on concern the application and evaluation of the content. Peter & Grivas note that the literature does not have collaboration data as a specific content category, but for some applications it does make sense to specify collaborative used information as collaborative data. This data is necessary for actors when they are collaborating towards a common goal.

According to Peter & Grivas, the data-relation modelling method supports the construct and configuration components of the 6C framework. The model gives insights to the kind of data which is exchanged as well as to what kind of infrastructure the interfaces between the actors need to have. Additionally, it provides understanding on the intercompany work-flows and to which level they are configured.

Service-based data-relation modelling method

Peter & Grivas propose that if the industry decides to introduce a service platform for its ecosystem, a service-based data-relation layer for the final model is required. This layer illustrates the future situation for an industry ecosystem with a service-based platform, on which intercompany workflows can be performed more efficiently.

The evaluation of the service-based industry ecosystem data-relation modelling method confirms increase of simplicity and transparency within the industry ecosystem by reduction of the number of relations. The highest amount of connections for an actor is two; one to the information exchange platform and one to the collaboration platform. Consequently, it is cost effective for each actor to have only two interfaces to manage, instead of multiples. If an actor wants to exchange information or collaborate with a new actor, no interfaces need to be set-up between them as they are already linked through the platform.

The Framework and Steps of the Business Ecosystem Modeling

Ma[137] has made an extensive literature review on business ecosystem modelling. Figure below presents the framework and main modelling steps Ma has identified. The modelling approach follows the same principles as the previous ones, starting from the indentification of system boundaries and major actors in the ecosystem and progressing through analysis of interaction between actors towards simulating the impacts of potential changes.

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[136] Peter, Marco and Grivas, Stella Gatziu (2017) An Approach to Model Industry Ecosystems - Enabling an Ecosystem for Service Platforms. Published in ICServ17 – The 5th International Conference on Serviceology.

[137] Ma, Zheng (2019). Business ecosystem modeling- the hybrid of system modeling and ecological modeling: an application of the smart grid. Energy Informatics (2019) 2:35, https://doi.org/10.1186/s42162-019-0100-4

Part	Stage	Business ecosystem modeling
Part I Business ecosystem architecture development	1	Identify the boundary of a selected ecosystem.
	2	Identify actors and their roles in the ecosystem.
	3	Identify actors' value propositions and business models.
	4	Identify interaction between actors (different types of interactions.)
Part II Factor analysis	1	Investigate influential factors and their impact on the elements in the ecosystem (actors, roles, and interaction.)
	2	Investigate potential changes in the ecosystem.
Part III Ecosystem simulation and reconfiguration	1	Multi-agent based ecosystem modeling to identify ecosystem reaction towards the potential changes.
	2	Ecosystem reconfiguration (including reconfiguration of actors, roles, and interaction) due to changes, system dynamics modeling might be applied at this stage.
	3	Business model reconfiguration.

Figure 16: The framework and steps of the business ecosystem modelling[138].

Ma goes further to analyse business ecosystems modelling with the integration of system modelling and ecosystem theories (Figure 16 & Figure 17). They propose a framework, which includes three parts and nine stages that combine theories from system engineering, ecology, and business ecosystem. Part I-Business ecosystem architecture development includes four stages which aims to identify a target business ecosystem and its elements (actors, roles, and interactions). Part II-Factor analysis includes two stages to identify potential changes (and the dimensions of the changes) in the ecosystem. Part III-Ecosystem simulation and reconfiguration aims to use simulations to investigate the transition of an ecosystem and the re-configurated ecosystem.

[138] Ma, Zheng (2019). Business ecosystem modeling- the hybrid of system modeling and ecological modeling: an application of the smart grid. Energy Informatics (2019) 2:35, https://doi.org/10.1186/s42162-019-0100-4

Business ecosystem modeling	Business ecosystem	System engineering	Ecology
Part I- Stage 1 Identify the boundary of a selected ecosystem.	Domain oriented business ecosystem. Innovation ecosystem. Digital ecosystem.	Ontology development. System architecture .	Types of ecosystem. Ecosystem hierarchy.
Part I- Stage 2 Identify actors and their roles in the ecosystem.	Stakeholders. Business models.	Domain ontology. System standards.	Categories of organisms (Lundberg and Moberg 2003)(producers, consumers, decomposers.) Types of keystone species (Mills et al. 1993) (predators, mutualists, engineers.)
Part I- Stage 3 Identify actors' value propositions and business models.	Business model (Zott and Amit 2013). Value creation (Clarysse et al. 2014).	Business services. Value stream.	Ecosystem function and biodiversity (Duffy 2002).
Part I- Stage 4 Identify interaction between actors (different types of interactions.)	Value co-creation. Value flows (Matthies et al. 2016) (monetary, product, information and intangible.) Social network analysis (Ashton 2008).	Flows (e.g., information exchange.) Associations (in UML diagram.) Service-oriented architecture (in TOGAF.)	Intra-specific & inter-specific ecological interaction. Ecosystem services Matter, energy and information flows.
Part II- Stage 1 Investigate influential factors and their impact on the elements in the ecosystem (actors, roles, and interaction.)	–	Motivation and strategy (in ArchiMate.) System thinking (Rubenstein-Montano et al. 2001). machine logic (Polic and Jezernik 2005).	Assessment and indicator of ecosystem conditions.
Part II- Stage 2 Investigate potential changes in the ecosystem.	Emergence and co-evolution (Peltoniemi and Vuori 2004b).	Risk management/ assessment (Sage and Rouse 2014).	Ecosystem change (Elmqvist et al. 2003).
Part III- Stage 1 Multi-agent based ecosystem simulation to identify ecosystem reaction towards the potential changes.	Multi-agent-based models (Lurgi and Estanyol 2010).	System dynamics (Karnopp et al. 2012).	System dynamics Multi-agent based modeling.
Part III- Stage 2 Ecosystem reconfiguration (including reconfiguration of actors, roles, and interaction) due to changes.	Business ecosystem lifecycle (Rong et al. 2015).	System lifecycle management (Sage and Rouse 2014).	Evolution of ecosystems (Azaele et al. 2006).
Part III- Stage 3 Business model recofiguraation.	Business model innovation (Chesbrough 2010).	–	–

Figure 17: The business ecosystem modelling with the integration of system modelling and ecosystem theory[139].

[139] Ma, Zheng (2019). Business ecosystem modeling- the hybrid of system modeling and ecological modeling: an application of the smart grid. Energy Informatics (2019) 2:35, https://doi.org/10.1186/s42162-019-0100-4

Business ecosystem modelling and enterprise architecture

From Enterprise architecture to business ecosystem architecture

Drews & Schirmer[140] have studied business ecosystems from the enterprise architecture viewpoint and how the architecture can develop from single enterprise to consider the whole business ecosystem. They have identified five stages between Enterprise Architecture Management (EA/EAM) and Business Ecosystem Architecture Management (BEA/BEAM) (see figure below).

Their first stage describes EA and EAM as it is generally understood in the literature with an internal perspective of single organizations[140]. In the second stage, external entities like customers, partners, and suppliers are included into the EA of a central actor. These entities are connected to the business layer of the EA. Therefore, additional concerns such as business models, innovative channels to the customer, and supply chains that include partners or customers can be addressed by the extended EA. Drews & Schirmer mention TOGAF 9.1 as an example of this kind of model, but also note that they are not yet used intensively when defining EA concerns [6] or EAM management practices.

The third stage Drews & Schirmer call a federated or collaborative network architecture (FA/CNA). There the actors involved might agree on exchanging and aligning certain parts of their architectures ("boundary architectures"). Information is shared to discuss common initiatives for improving the situation for all participants. A central player might take a leading role and get the mandate to organize this information exchange.

Drews & Schirmer call the fourth stage focused business ecosystem architecture (FBEA). They define that in this stage, a central actor decides to analyze details of its customers', partners' or suppliers' EA in order to plan and accomplish interventions that will affect these actors. However, they also note that the analysis does only include the EA of selected actors (from a whole actor class). The different EA of customers may be analyzed by selecting a representative actor or actors from each customer segment[140]. This information can be used for defining a platform initiative (to either win competitors to become partners or estimate the possible success of the initiative/intervention) to become a keystone player in the respective ecosystem[140]. In successfully intervening with a platform initiative, interfaces, standards and processes have to be aligned with those of its customers and partners.

In the fifth stage in the Drews & Schirmer model, a central actor is willing to or has the obligation to get an overview on a whole ecosystem. They call this stage the business ecosystem architecture and it differs from the 4th stage in that it requires the analysis and overview of the whole ecosystem instead of only a few selected actors and their individual architectures.

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[140] Drews, P., Schirmer, I. (2014). "From Enterprise Architecture to Business Ecosystem Architecture", *2014 IEEE 18th International Enterprise Distributed Object Computing Conference Workshops and Demonstrations*, pp. 13-22, 2014.

TABLE I. STAGES FROM EA TO BEA

Stage	(Extended) Focus
Enterprise Architecture (EA)	core business, internal focus
Extended Enterprise Architecture (EEA)	EA + customers, partners, and suppliers – modeled and managed from a focal actor's perspective
Federated or Collaborative Network Architecture (FA/CNA)	EEA + several actors in a network are exchanging selected parts of their EA and negotiate about standards, interfaces, inter-organizational processes, etc. due to a common interest or project
Focused Business Ecosystem Architecture (FBEA)	FA/CNA + EA of selected customers, partners, and suppliers / reference EA, to-be/reference EA of customers modelled by a software vendor
Business Ecosystem Architecture (BEA)	FBEA + general overview of infrastructure and interfaces to all connected EA, including details of many actors' EA

Figure 18: Stages from EA to BEA[141].

Also Wieringa et al.[142] note that the assumption of central governance makes EA frameworks like TOGAF (The Open Group Architecture Framework) unsuitable for network organizations that do not have a central coordinator. They point out that during the past two decades there has been a rapid growth of network organizations, which has been facilitated by the new technologies such as internet, web technology, mobile technology, RFID and the Internet of Things. Currently, blockchain technology, big data and machine learning drive growth further. According to Wieringa et al. these technologies enable companies to outsource some of their value activities to third parties, to bundle products with complements, to offer online platforms to producers and consumers, to buy information-intensive services from others, and to decentralize their organizations.

Wieringa et al. point out the challenge of aligning business and IT systems in this kind of networks that have no central governance but are, nevertheless, IT enabled. Each member of the network has its own business goals and legitimately looks after its own interests. Each member has the freedom to do something else. Wieringa et al. approach the aligment challenge by integrating different frameworks for the analysis of ecosystems, coopetition,

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[141] P. Drews, I. Schirmer, "From Enterprise Architecture to Business Ecosystem Architecture", *2014 IEEE 18th International Enterprise Distributed Object Computing Conference Workshops and Demonstrations*, pp. 13-22, 2014.
[142] Wieringa R.J., Engelsman W., Gordijn J., Ionita D., "A Business Ecosystem Architecture Modeling Framework", *Business Informatics (CBI) 2019 IEEE 21st Conference on*, vol. 01, pp. 147-156, 2019

coordination and value models into a model of decentralized business-IT alignment with a decentralized governance game.

The Ecosystem Architecture Management (TEAM) framework

Wieringa et al.[143] introduce their TEAM framework, which consists of nine sets of questions about the architecture of the ecosystem and three sets of questions about the decentralized business ecosystem architecture, grouped in three layers: strategic view, value modeling view, and technology view (Figure below). According to them, by answering the questions regarding the three architectural layers enables creating an overview of business-IT alignment in the ecosystem architecture. Following sub-chapters give an overview of the different layers.

Strategy Layer

According to Wieringa et al. the strategic view of a company on an ecosystem it participates in is concerned with the customer needs to be satisfied, and with the participants of the ecosystem. The participants are the suppliers and complementors who the company needs to satisfy those needs, competitors who try to do the same, and the rule makers that provide boundaries and associations that provide communication mechanisms for the participants of the ecosystem.

After identification of the customer needs and participants, an assessment whether each participant adds value to the system needs to be done, i.e. value activities that contribute to the satisfaction of customer needs must be identified. Each player has capabilities to perform value activities, but for any actor its capabilities are limited. This is essential for playing the coopetition game and also a necessary preliminary for the value modeling task at the tactical level.

When modeling an ecosystem as-is, the value activities that the participant actually deliver must be identified[144]. When redesigning an ecosystem, a participant may decide to reallocate them by outsourcing, or to bring in new value-adding participants.

In the TEAM framework Wieringa et al. view decentralized governance as a coordination game where participants must consider coordination paradigms. Wieringa et al. suggest that decentralized coordination may be market-based using only price as coordination mechanism, but more likely there will also be a relational paradigm based on shared norms and values. There may also be some hierarchy aspect as some participants are more powerful than others.

When assessing the ecosystem coordination, a participant should consider the source of legitimate authority (written agreements such as the law and contracts, the force of tradition, or a mix of them), and mechanisms to resolve conflicts[145]. Written and unwritten agreements must be considered, and the cost of switching to another transaction partner

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[143] Wieringa R.J., Engelsman W., Gordijn J., Ionita D., "A Business Ecosystem Architecture Modeling Framework", *Business Informatics (CBI) 2019 IEEE 21st Conference on*, vol. 01, pp. 147-156, 2019

[144] Ibid.

[145] Ibid.

must be assessed. Wieringa et al. note that this is influenced by, e.g. the level of standardization in the ecosystem, which they consider a technical governance game.

In the Wieringa et al. framework the normative environment created by rule makers, as well as formal and informal communication mechanisms created by associations, provide the boundaries and mechanisms with which to achieve a company's goals in the ecosystem. Some of this can be influenced by the players of the game[146].

Value Model

According to Wieringa et al. the viability of an ecosystem is determined not only by the extent to which it meets customer needs, but also by the perceived fairness of the distribution of cost, benefits and risk over the participants. If players become aware that costs are made by one set of actors but benefits are reaped elsewhere, then the system may disintegrate.

It is essential that each player have positive revenue. Wieringa et al. suggest that a model should be built that consists of a map of commercial transactions, and checking it for reciprocity of all transactions. In terms of the value network, reciprocity means that there must be no transaction where all value flows in one direction only. They also suggest that cash flow scenarios can be simulated based on assumptions about customer need and prices. According to Wieringa et al. each player in the system can make a model like this, and in their negotiations they may share some parts of their own value model of the ecosystem with others[147].

Technology Architecture

Wieringa et al. suggest in their framework that at the technology level data sharing requirements across participants should be looked at. They propose that e.g., semantics for shared data, as well as confidentiality, availability and integrity requirements must be specified and agreed on data that is accessed cross-organizationally. Additionally, they point out thet if transactions are automated, agreements must be made on who validates them, if valid transactions can be refused, and on finality of transactions.

Regarding coordination activities, Wieringa et al. call for the actors to agree coordination requirements about transaction details and the coordination process. According to Wieringa et al. the coordination analysis considers trust assumptions as well as physical movement of goods. The IT requirements part of the Wieringa et al. framework considers e.g. application interoperability requirements and cybersecurity risks for example if there is participation in an online network. Technological coordination is concerned with IT standards chosen for the network, and update procedures that the actors agree among each other[148].

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146 Wieringa R.J., Engelsman W., Gordijn J., Ionita D., "A Business Ecosystem Architecture Modeling Framework", *Business Informatics (CBI) 2019 IEEE 21st Conference on*, vol. 01, pp. 147-156, 2019

147 Ibid.

148 Ibid.

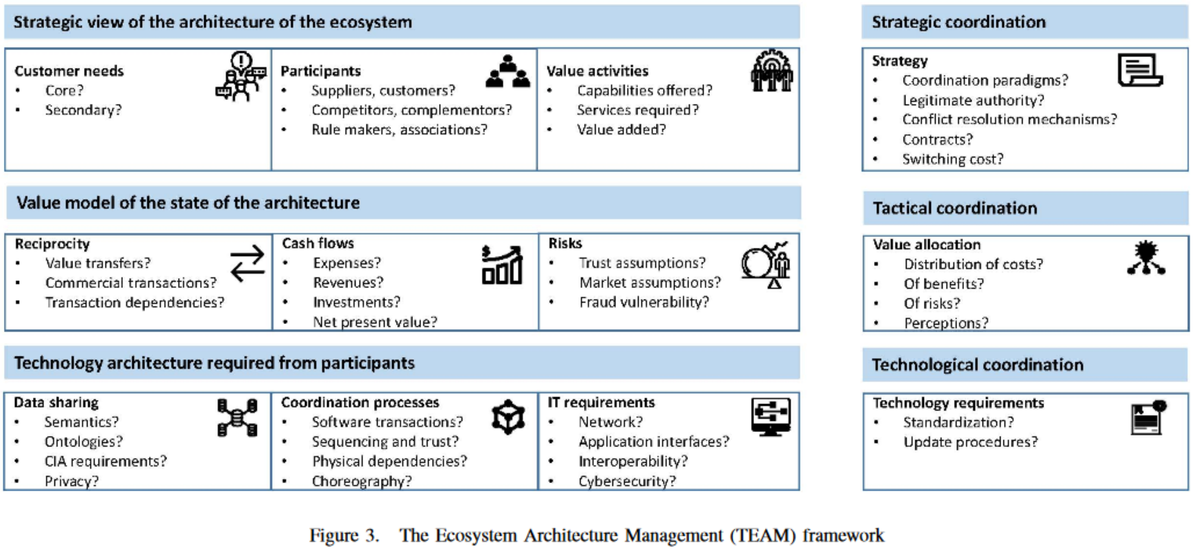

Figure 19: A Business Ecosystem Architecture Modeling Framework by Wieringa et al.[149].

Value network analysis

It has been well established that network analysis can be used to describe work groups, organizations, business webs, and other purposeful networks where both tangible and intangible value exchanges support the achievement of specific outcomes[150]. The value network can be seen as a series of inter-twined value chains where some nodes are simultaneously involved in more than one value chain[151]. A particular strategy or business model formulated within the context of one value chain may at the same time be inappropriate, or even harmful, in the context of the other value chains of which these nodes are part.

The working hypothesis for value networks is that network analysis and organizational performance could be more tightly linked if network analysis is significantly expanded to include financial and non-financial asset utilization, value conversion and realization dynamics and flows, linkages to business processes and intellectual capital, and network indicators that clearly link to organization and market-level performance[150]. These analytical approaches very specifically seek insights into the question of exactly how purposeful networks (such as organizations, cross-boundary task networks, public agency collaborations, and societal change networks) can more effectively create value, achieve business outcomes, and generate sustainable success[150].

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[149] Wieringa R.J., Engelsman W., Gordijn J., Ionita D., "A Business Ecosystem Architecture Modeling Framework", *Business Informatics (CBI) 2019 IEEE 21st Conference on*, vol. 01, pp. 147-156, 2019

[150] Allee, V. (2009). Value-creating networks: Organizational issues and challenges. Learning Organization, 16(6), 427–442. https://doi.org/10.1108/09696470910993918

[151] Li, F., & Whalley, J. (2002). Deconstruction of the telecommunications industry: from value chains to value networks. Telecommunications Policy, 26(9–10), 451–472. https://doi.org/10.1016/S0308-5961(02)00056-3

Participants in a value network, either individually or collectively, utilize their tangible and intangible asset base by assuming or creating roles that convert those assets into more negotiable forms of value that can be delivered to other roles through the execution of a transaction. In turn, the true value of deliverables received is realized by participants when they convert them into gains or improvements in tangible or intangible[152].

According to (Allee, 2009) Value Network Analysis fills the analytical gap between other organizational performance tools, such as organization charts, asset management, business process modeling and social networks (fig. below).

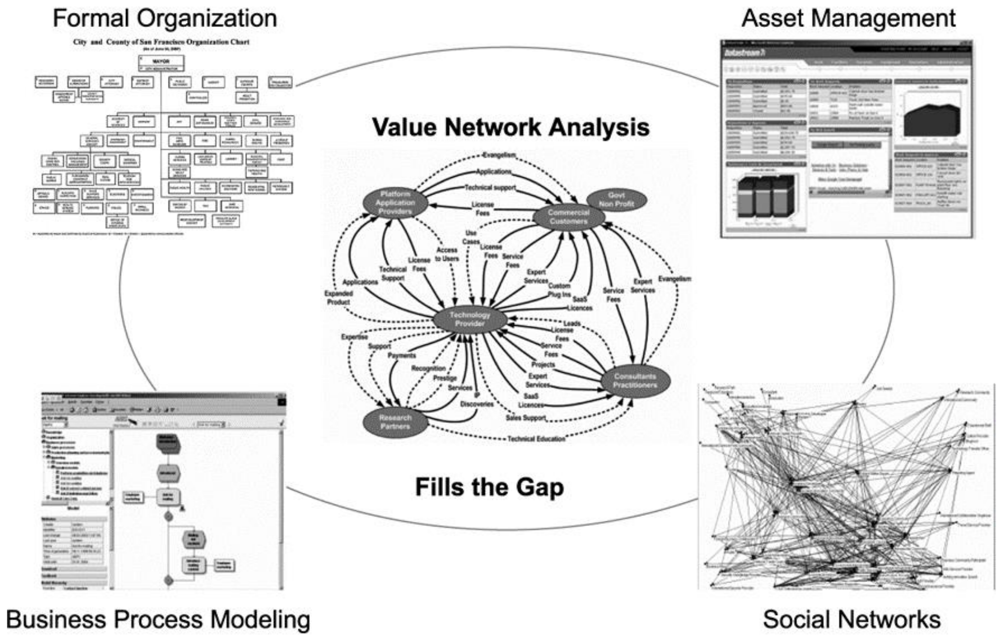

Figure 20: VNA fills the gap between other organizational performance tools[152].

Peppard & Nylander[153] suggest that the aim of NVA is to generate a comprehensive description of where value lies in a network and how value is created. According to them Network Value Analysis has the following basic steps:

1. Define the network
2. Identify and define network entities
3. Define the value each entity perceives from being a network member.
4. Identify and map network influences.
5. Analyse and shape.

[152] Allee, V. (2008). Value network analysis and value conversion of tangible and intangible assets. Journal of Intellectual Capital, 9(1), 5–24. https://doi.org/10.1108/14691930810845777
[153] Peppard, J., & Rylander, A. (2006). From Value Chain to Value Network:: Insights for Mobile Operators. European Management Journal, 24(2–3), 128–141. https://doi.org/10.1016/J.EMJ.2006.03.003

According to Allee[154] Value network analysis (VNA) links specific interactions within the value creating network directly to financial and non-financial scorecards. It does the following:

- provides a fresh perspective for understanding value creating roles and relationships, both internal and external, upon which an organization depends;
- offers dynamic views of how both financial and non-financial assets can be converted into negotiable forms of value that have a positive impact on those relationships;
- explains how to more effectively realize value for each role and how to utilize tangible and intangible assets for value creation; and
- provides a systematic analysis of how one type of value is converted into another.

According to Allee[154] participants in a value network, either individually or collectively, utilize their tangible and intangible asset base by assuming or creating roles that convert those assets into more negotiable forms of value that can be delivered to other roles through the execution of a transaction. In turn, the value of deliverables received is realized by Value network analysis participants when they convert them into gains or improvements in tangible or intangible assets. The value conversion strategy model in Figure below illustrates this value conversion.

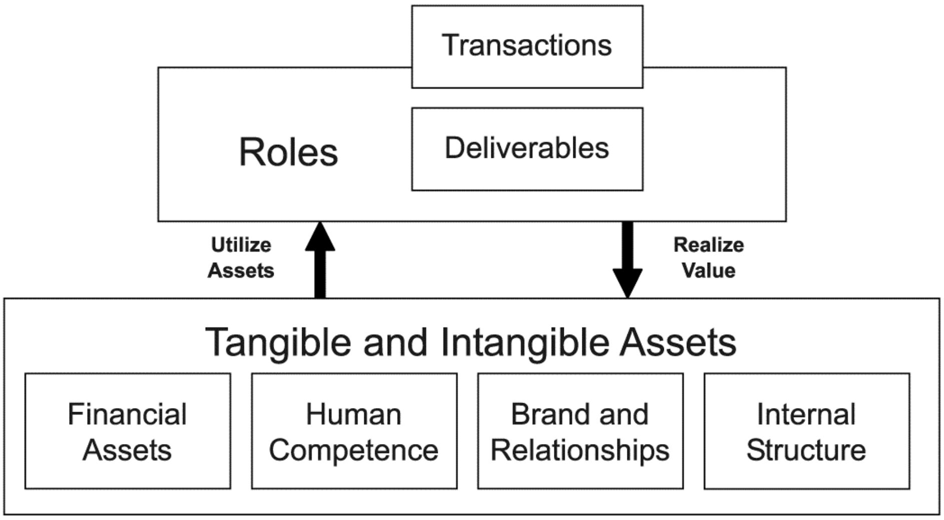

Figure 21: Value conversion strategy model[154].

Developing a value network strategy requires understanding the shared purpose and values of the network, after which an actor can study and choose the role it wants to play in the network. The emergent purpose and values of the network are revealed through the pattern of roles and value exchanges in service to fulfilling an economic or social goal or output[154]. The shared purpose and values, being either tacit or explicit, can be deduced from the network patterns. Value for each actor is continuously negotiated in the context

[154] Allee, V. (2008). Value network analysis and value conversion of tangible and intangible assets. Journal of Intellectual Capital, 9(1), 5–24. https://doi.org/10.1108/14691930810845777

of overall purpose and values of the network. Sustainability of the network depends on the existence of a high level of both transactional and network perceived value. Figure below builds on the Figure above by depicting the value conversion strategy of a group of participants into the fabric of the value network itself[155].

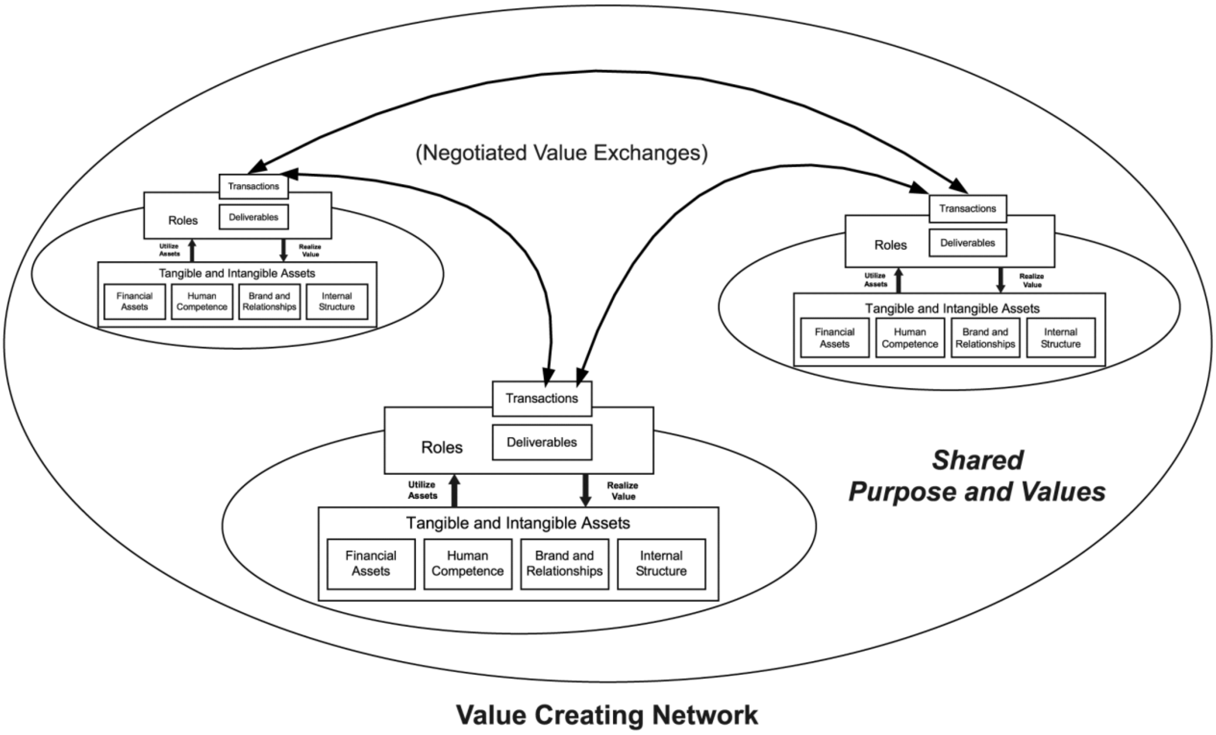

Figure 22: Value network strategy model[155] .

To model a value network one should first map out the value exchanges across the network[155]. This mapping method has three elements – roles, deliverables, and transactions:

1. *Roles* are real people or participants in the network who provide contributions and carry out functions. Participants have the power to initiate action, engage in interactions, add value, and make decisions. They can be e.g. companies, business units, or team.
2. *Transactions*, originate with one participant and end with another. They are represented as arrows between two roles and can be formal contract exchanges around product and revenue, or intangible flows of market information and benefits.
3. *Deliverables* are the actual “things” that move from one role to another. A deliverable can be physical (e.g. a document or a table) or non-physical (e.g. a verbal message or a specific type of knowledge, expertise, or advice).

After critical roles, value exchanges and transactions have been identified it is possible to do full value network analysis. Analyzing a value network requires addressing three basic questions[155]. The first question is about assessing the value dynamics, health and vitality,

[155] Ibid.

and value conversion capability of the system as a whole. The second and third questions concentrate on each specific role as it relates to value conversion. The basic questions are[156]:

1. *Exchange analysis* – What is the overall pattern of exchanges and value creation in the system as a whole? How healthy is the network and how well is it converting value?
2. *Impact analysis* – What impact does each value input have on the roles involved in terms of value realization?
3. *Value creation analysis* – What is the best way to create, extend, and leverage value, either through adding value, extending value to other roles, or converting one type of value to another?

System dynamics modelling

Lagazio et al.[157] have studied the impact of cyber-crime on the financial sector utilizing system dynamics modelling. First, they state that not all cyber-crimes can be fully assessed and understood through an economic perspective. They suggest that economic considerations are less prominent e.g. in case of ideological attacks, revenge and other crimes of passion where the attacker has no financial motivation[157]. Lagazio et al. also suggest that because of its complex nature, assessing the impact of cyber-crime has been characterized by e.g. the following controversies and criticisms:

- Studies sponsored by the security industry have been criticized for e.g. obscure methodology, vested interests, and extrapolation errors due to asymmetric responses in samples which are heavily biased towards people without direct cyber-crime exposure.
- Most of the studies on the impact of cyber-crime have produced no robust and replicable findings. The reason can be e.g. inadequate and/or inaccurate data, different specifications or theories, complexity, or simply random variation.

These different debates have raised questions concerning which data, methods and techniques should be developed to capture the complex issues of 'economics of security'[158]. Lagazio et al. point out that these methods have typically focused at the level of the individual company and organization without analyzing the economic cost on the entire value network and society at large. Only fairly recently the impact of specific security incidents across the value network, taking into account second-round effects, have been started to study. While addressing several issues of previous cost models, these more recent attempts have also opened up further challenges[159]. Second-round impacts are not easy to assess and often require an attempt to assess implicit costs, which are difficult to measure unambiguously.

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[156] Ibid.
[157] Lagazio, M., Sherif, N., & Cushman, M. (2014). A multi-level approach to understanding the impact of cyber crime on the financial sector. Computers & Security, 45, 58–74. https://doi.org/10.1016/J.COSE.2014.05.006
[158] Ibid.
[159] Ibid.

Lagazio et al. [160] propose that system dynamics (SD) in general, and especially causal loop diagrams (CLD), are suitable choices for modelling the impact of cyber-crime for the following reasons:

- An SD approach is widely recognized as a clear method for communicating ideas and complex structures to those with little working knowledge of the particular problem studied.
- The economic variables involved appear to follow feedback structures more closely than linear causal relationships. Some of these causal relationships also seem to be characterized by delayed effects, which can be well represented by a SD model.
- Because of the lack of comprehensive and robust data on cyber-crime, CLDs can offer a useful alternative to more data-driven models. They enable initial development of CLDs for cyber-crime with limited data, which can then be further elaborated when there is more data available. I.e. SD facilitates incremental model development and learning by providing new insights to the problem while refining the model with new data.

Lagazio et al. define the following three main categories for cyber-crime costs:

1. *Direct losses*: monetary losses, damage, or other suffering experienced by the targeted end users and organizations as a consequence of a cyber-crime.
2. *Indirect losses*: the monetary losses and opportunity costs imposed on organizations and society when a cyber-crime is carried out, no matter whether successful or not.
3. *Defense costs*: direct defense costs of development, deployment and maintenance of cyber-crime measures and indirect defense costs arising from inconvenience and opportunity costs caused by the defense measures.

According to Lagazio et al. the most common approach in developing SD models is initially to map the dynamic relationships that are at stake within a system, or specific problem of interest, and then use a variety of methods to understand the possible consequences of those relationships, while developing theories about them. CLDs are causal diagrams that aid visualization of how interrelated variables affect one another. Typical causal-loop diagrams define causal links (i.e., relationships) representing causes and effects. The CLD diagram consists of a set of nodes representing the key variables of a complex system, connected together via links. These links, visualized by arrows, can be labelled as positive or negative. A positive causal link means that the two nodes, or variables, change in the same direction e.g. if the node in which the link starts decreases, the other node also decreases. By contrast, a negative causal link means that the two nodes change in opposite directions. The effects may also be delayed.

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[160] Lagazio, M., Sherif, N., & Cushman, M. (2014). A multi-level approach to understanding the impact of cyber crime on the financial sector. Computers & Security, 45, 58–74. https://doi.org/10.1016/J.COSE.2014.05.006

3.1.2. Modelling Approaches Towards Cyber Ecosystems

Comprehensive technical and organizational security measures, requiring also the involvement of the human factor, have always been an important part for the protection of the company's infrastructure from threats that could, intentionally or not, cause damage to the whole environment. The security considerations related to the individual company, rarely to an entire network, and focused on the critical information of a company on premise. With the increasing digitalization of business processes, facilities and company divisions were connected that had no or only very inadequate security measures. Systems were connected into a worldwide network whose functionality was almost entirely considered from an economic and not a security perspective. This vulnerability became increasingly obvious over time, also driven by several events.

One of the security measures in an internally networked but externally decentralized environment that had only a few nodes to the digital periphery, was the classic firewall as perimeter defense. Critical data on intellectual property (IP), sensitive customer information or business activities was protected by isolation from external threat actors, as they were generally stored in separate in-house databases and networks[161]. Thus, virtual perimeter security systems were quite effective as they protected the integrity of access to databases.

Advances in technology have created entirely new business models for organizations based on the better collection and analysis of data and the actions taken. This has created a complex community of interacting devices, networks, people and organizations in an environment of processes and technologies that support these interactions, known as cyber ecosystem. This cyber ecosystem creates an entirely new value chain and has enormous benefits for the economy and society, but at the same time it also carries numerous risks.

The increase in the number of connections to external networks created new vulnerabilities and provided new opportunities for malicious activities, as sensitive data was no longer isolated in the corporate network, but was shared with various parties and was sometimes distributed in an obscure manner[162]. As a result, perimeter defense reached its limits and new concepts were needed.

The implementation of the "defense-in-depth" security model ensured that if the perimeter defense of the company was breached, additional security tiers within the network could prevent critical information from being immediately accessed by cyber-criminals[163]. With each additional node, however, the vulnerability increased as well. In a growing cyber ecosystem with innumerable interconnected stakeholders, it becomes apparent that security is not an individual, but an overall task of the ecosystem. Thus, the limitations of traditional security defense become apparent.

In modern factory environments, it is no longer sufficient to simply ensure individual security. A holistic approach is necessary, which on the one hand identifies relevant and

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[161] Ernst & Young, "Achieving Resilience in the Cyber Ecosystem – Insights on Governance, Risk and Compliance", Report, 2014, [Online]. Available: https://www.ey.com/Publication/vwLUAssets/cyber_ecosystem/$FILE/EY-Insights_on_GRC_Cyber_ecosystem.pdf [Accessed 18 03 2020].
[162] Ibid.
[163] Ibid.

particularly vulnerable areas on the individual and network level in the ecosystem, and in a next step establishes common control and security mechanisms in the cyber ecosystem. This involves the following steps:

- Mapping internal and external relationships
- Identifying essential (tangible and intangible) assets and the related interdependencies, threats and vulnerabilities (risk factors)
- Considering besides known, also unknown and uncontrollable factors influencing the cyber ecosystem
- Establishing joint control and security mechanisms

A properly functioning supply chain in the Factory of the Future is of fundamental importance to the cyber ecosystem and is thus challenged by substantial risks, which are discussed in the following.

Cyber Risk in Supply Chains

Physical supply chain security, as originally defined, is dominated by the movement of products, finances and information[164]. In contrast, a cyber supply chain consists of a chain of technologies in a digital (IT) environment designed to exchange, connect and build data in virtual networks[165]. Risk mitigation stakeholders in any sector may be inclined to deal with cybersecurity in the same way as with deterministic problems. The introduction of dedicated IT-security products to protect systems could be considered a purely technical application and solution to the problem. However, this would ignore the complexity and adaptability of cyber threats, which require different layers of security (technical, human, organizational) and would not have a sustainable effect. Similarly, it is highly unlikely that an organization would have a complete overview of potential vulnerabilities (of the overall system architecture) underlying its actions, given the rising number of inter-system links across stakeholders and regions.

Many systems that operate manufacturing/shop floor processes have grown historically and were never designed to be connected to complex systems that span beyond corporate networks. Furthermore, exponentially growing amounts of data provide opportunities for optimization of processes or even new business models, which can only be utilized efficiently by increasing networking. In order to improve shop floor processes to meet growing demands, data and isolated systems will require more interconnection. The progressive transition from traditional control systems to improved monitoring and communication systems in modern data networks will significantly change safety assessments.

However, this makes legacy systems that were rarely considered and developed from a security but rather from a safety perspective vulnerable and could provide a gateway to malicious actors. This system integration will lead to expanded supply chains in which each party is dependent on the services of their counterparts. More stakeholders and systems

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[164] H. Peck, “Reconciling Supply Chain Vulnerability, Risk and Supply Chain Management”, *International Journal of Logistics Research and Applications*, 2019, Vol. 9 No. 2, pp. 127-142.
[165] G. E. Smith, K. J. Watson, W. H. Baker and J. A. Pokorski II, “A Critical Balance: Collaboration and Security in the IT-enabled Supply Chain”, *International Journal of Production Research*, 2007, Vol. 45 No. 11, pp. 2595-2613.

render each part of the chain relevant, as measures can only be effective in their entirety if a holistic approach is taken at technical, organizational and procedural level. In the following, models for risk management in cyber supply chains are outlined.

Cyber Supply Chain Risk Management

Cyber supply chain risk management (CSCRM) is the outcome of a research project by the Robert H. Smith School of Business Supply Chain Management Center for the National Institute of Standards and Technology. It is defined as the "organizational strategy and programmatic activities to assess and mitigate risks across the end-to-end processes (including design, development, production, integration, and deployment) that constitute the supply chains for IT networks, hardware, and software systems"[166]. The research project was a response to support IT executives addressing the risks of an increasing globalized and interconnected supply chain, which leads to an integration of various hard- and software systems. It comes back to the question of how to gain control of the cyber supply chain while there is a process of defragmentation going on.

The focus of CSCRM is specifically on the cyber supply chain that is part of a defined business ecosystem with distinct responsibilities for the involved actors (view figure). The cyber supply chain can be defined as "the entire set of key actors and their organizational and process-level interactions that plan, build, manage, maintain, and defend the IT system infrastructure"[167]. According to Goertzel, this includes processes, products (including intellectual property) and their respective flows, all involved data (e.g. supply chain management data) and their respective flows and the participants – ergo – people.[168]

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[166] S. Boyson, "Cyber Supply Chain Risk Management: Revolutionizing the Strategic Control of Critical IT Systems, *Technovation*, 2014, Vol. 34 No. 7, pp. 342-353, p. 343.
[167] Ibid., p. 345.
[168] K. Goertzel, "Supply Chain Risk Management and the Software Supply Chain", Presentation at OWASP AppSec DC Conference, 2010, [Online], Available: https://wiki.owasp.org/images/7/77/BoozAllen-AppSecDC2010-sw_scrm.pdf [Accessed 21 04 2020].

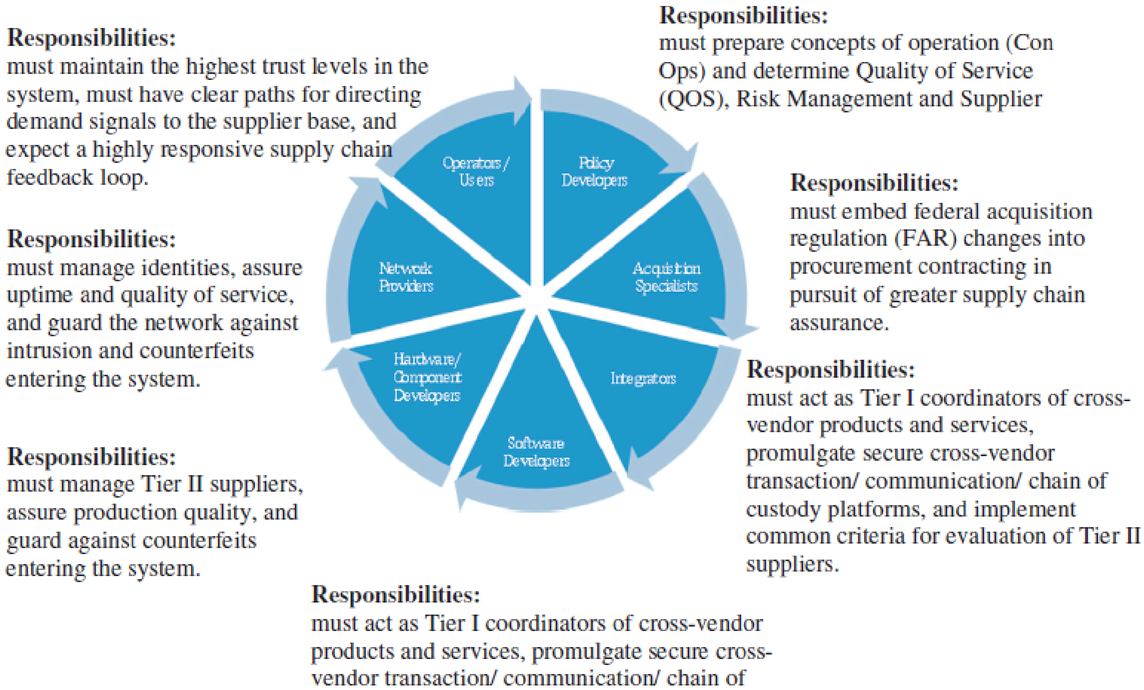

Figure 23: The Cyber Supply Chain Ecosystem[169].

CSCRM combines as a hybrid management construction the strategies of three disciplines in an interdisciplinary approach:

- **Enterprise Risk Management** is defined as "a process, effected by an entity's board of directors, management, and other personnel, applied in strategy setting and across the enterprise, designed to identify potential events that may affect the entity, and manage risks to be within its risk appetite, to provide reasonable assurance regarding the achievement of entity objectives"
- **Supply Chain Management** "is an integrating function with primary responsibility for linking major business functions and business processes within and across companies into a cohesive and high-performing business model. It includes all logistics management activities as well as manufacturing operations, and it drives coordination of processes and activities within and across marketing, sales, product design, finance, and information technology"
- **Cybersecurity** constitutes "the body of technologies, processes, and practices designed to protect networks, computers, programs, and data from attack, damage, or unauthorized access"[170].

The aim behind is it to use the advantages of all approaches, while mitigating the blind spots and disadvantages. CSCRM seeks to engage both managerial and human factors engineering in preventing risks from disrupting IT systems' operations. Unlike

[169] S. Boyson, T. Corsi and H. Rossmann, "Building A Cyber Supply Chain Assurance Reference Model", Report, 2009, [Online], Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.363.1516&rep=rep1&type=pdf [last accessed: 21 04 2020].
[170] S. Boyson, "Cyber Supply Chain Risk Management: Revolutionizing the Strategic Control of Critical IT Systems, *Technovation*, Vol. 34 No. 7, pp. 342-353, p. 343.

enterprise risk management alone, it is not focused on a top-down control mechanism for relatively static business environments, but rather seeks to address the fundamental dynamism and real-time, world scale of adaptive IT networks. In the optimal case, this leads to a strengthening of the defense in depth by covering the entire life cycle of a supply chain system as well as in breath by expanding the supply chain system. Overall, this would also lead to more control over one's supply chain. More control supports the task of a company to mitigate risks and can mean possible sooner recovery with less damages due to an incident.

Table 3: SCRM Community Framework Tiers and Attributes after Boyson[171] - own illustration

Tier I	Risk Governance: (UMD / SCOR)	Executive Risk Governance Group
		Extended Enterprise Risk Assessment
		Extended Enterprise Risk Mitigation Strategy
		Extended Enterprise Risk Monitoring
Tier II	System Integration: (UMD / SCOR)	System Lifecycle Integration / Design for Risk
		System Risk Assessment / Threat Modeling
		Acquisition Risk Assessment / Sourcing Management
		Supply Chain Network Modeling / Mapping
		Tracking and Visibility of Supply Chain Components
		Program / Project / Process Risk Auditing / Monitoring
Tier III	Operations: (SCOR / UMD)	Risk Management Controls, by Process:
		Plan
		Design
		Make
		Source
		Deliver
		Return

A maturity/capability model was developed within the framework tiers and attributes as shown below. The model matches capabilities in the three tiers with maturity levels from emergent (level 0) to diligent (level 1) to proficient (level 2). The aim is to enable a data-

171 Ibid., p. 349.

driven and strategic code of practice of digital software supply chains. The model addresses security, resilience, integrity and quality aspects of the cyber supply chain.

Table 4: Capability/Maturity Model for Cyber Supply Chain Risk Management after Boyson[172] – own illustration.

Cyber-SCM Key Factors	Cyber-SCM Maturity Phase: Emergent *(Not implemented OR in planning stages)*	Cyber-SCM Maturity Phase: Diligent *(Limited or early enterprise implementation but shows steady effort to enact supply chain controls)*	Cyber-SCM Maturity Phase: Proficient *(Seasoned implementation and achievement of process improvements across the supply chain)*
Tier 1: Governance			
Responsibility for risk management	Limited to CIO shop	Involves multiple business units	Extensive, enterprise- and supply chain-wide
Interaction between CIO/ CSO and other key enterprise executives and supply chain partners	Nonexistent	Limited	Extensive
Enterprise risk management (ERM) program elements	Not defined	Defined and partially implemented	Fully defined and implemented
Systematic risk assessment activities	None	Selected risk assessment activities across the enterprise	Extensive supply chain-wide risk assessment act-ivities involving suppliers and customers
	Recommendations for Maturity Phases 1 and 2: Need to formalize risk management process with an executive organization, program charter and standardized techniques for risk assessment, prioritization and mitigation		
Tier 2: Systems Integration			
Security control of personnel, facilities, and processes	Due diligence/ background checks of new hires and facility access control	Periodic security reviews of current employees and periodic monitoring of physical and IT access logs	Constant due diligence of employees and contractors and suppliers; and continuous monitoring of extended enterprise physical and IT access logs
System risk management embedded as overarching contractual obligation	Not explicitly built into contracts	Explicitly built into contracts but not aggressively monitored or enforced	Explicitly built into contracts; aggressively monitored and enforced; consistent termination of out-of-

172 Ibid., p. 352.

for contractors and suppliers			compliance contractors and suppliers
Design of resilient systems via threat modeling and war gaming	Used sporadically to react to and address escalation in system threats	Used by internal enterprise personnel in proactively designing selective systems	Used as a critical design tool across all critical systems with key supply chain partners
Risk mitigation	Risks not identified and not assigned to specific personnel for mitigation purposes	Some risks identified and assigned for mitigation purposes, with sporadic follow-up	Continuous identification, assignation, mitigation, and monitoring of identified risks
Defense against IT supply chain breaches	Limited to IT perimeter defenses and intrusion detection	Broader IT system surveillance, including mechanisms such as proxy server code repositories for scanning/ detecting viruses	Real-time risk dashboards and sensor grids for global situational awareness of IT and physical supply chains
	Recommendations for Maturity Phases 1 and 2: Ramp up use of contractual mandates to increase contractor/ supplier disclosure and management of supply chain risk; need to establish risk registry to track risk mitigation activit ies		
Tier 3-Operations			
Validation of IT system components	Limited to compliance-level testing	System-wide quality assurance processes put into place	Full spectrum strategy to assure integrity of systems: use of embedded signatures, quarantining of suspect components, auditing of certificates of conformance
Software configuration management systems and hardware certificates of traceab ility	Compliance-level tracking	Attempts to maintain and audit completeness and accuracy of all product and component “pedigree” documents	Full-spectrum strategy to assure continuous visibility of software and hardware production/ delivery cycle through RFID, digital locks, video surveillance, tracking portals
Supplier qualification and operational checks	Frequent purchases on gray market; limited due diligence over suppliers	Pre-qualification of suppliers; limited screening of carriers	Comprehensive sourcing strategy and use of only known suppliers and trusted carriers
Protocols to deal with counterfeit parts	Case-by-case response to suspect parts	Built-in contract mechanisms to return suspect parts to suppliers	Pre-established relationships with customs authorities and the FBI; standard operating procedures to remove suspect parts from the supply chain

	Recommendations for Maturity Phases 1 and 2: Reduce liability by transitioning to trusted contractors, suppliers, and carriers; reducing or eliminating gray-market purchases; and creating policies for reporting and disposing of suspect parts		

This model serves as a guiding framework for best model practices by the U.S. National Institute of Standards and Technology, which are regularly updated and concretized for diverse industrial players as well as federal agencies[173].

However, Farooq and Zhu criticize that CSCRM does not take into account the increased complexity of an evolving Internet of Things (IoT) and Industrial Internet of Things ecosystem (IIoT), but is more relevant to a traditional ICT environment. They interject that there is a high vulnerability of the ecosystem of cyber-physical attacks due to the "integration of multiple devices and components that are designed and manufactured by different entities"[174]. They identify several key logistic challenges due to the highly decentralized nature of the IoT supply chain and ecosystem such as a lack of control over the upstream supply chain, an unwillingness of some suppliers to disclose supply chain information, as well as an unawareness of known vulnerabilities in combination with the unavailability of a centralized database to learn about these vulnerabilities[175].

A Conceptual Model for a Supply Chain Cyber Security System

The conceptual model for a supply chain cyber security system stems from an extensive literature review by Ghadge et. Al.[176]. It is the result of a systematic literature review of published papers from 1990 to 2017 across diverse disciplines with 41 final papers serving as the basis for the development of the model. The aim of the model is to support organizations to identify, classify, assess, mitigate – shortly to manage – cyber risks in supply chains while also giving practitioners a holistic model to better understand the cyber risks within supply chains. By doing so, the authors identified future research fields in order to increase cyber security as well as cyber resilience within supply chains.

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[173] See for example: J. Boyens, C. Paulsen, R. Moorthy and N. Bartol, "Supply Chain Risk Management Practices for Federal Information Systems and Organizations", Report, National Institute of Standards and Technology, 2015; J. Boyens, C. Paulsen, N. Bartol, K. Winkler and J. Gimbi, "Key Practices in Cyber Supply Chain Risk Management: Observations from Industry", Report, National Institute of Standards and Technology, 2020, [Online], Available: https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.02042020-1.pdf [Accessed 22 04.2020].
[174] M. J. Farooq and Q. Zhu, "IoT Supply Chain Security: Overview, Challenges, and the Road Ahead", *ArXiv* [pre-print], 2019, pp. 1-5, p.1.
[175] Ibid., p. 5.
[176] A. Ghadge, N. Caldwell, M. Weib and R. Wilding, "Managing Cyber Risk in Supply chains: A Review and Research Agenda", *Supply Chain Management* (ahead-of-print), 07 2019, pp. 1-36.

In Gadghe et. Al. point of view an extensively increased cyber supply chains security requires the alignment of the IT, organizational and supply chain systems. These systems have been identified in the literature review as enormous risk sources, in particular in their interlinkage with each other. Furthermore, all of these individual systems are linked to specific weak Points of Penetration (PoPs) on a technical, human as well as physical level. These diverse PoPs require distinct mitigation measures as can be seen in the triangles in the graphic below.

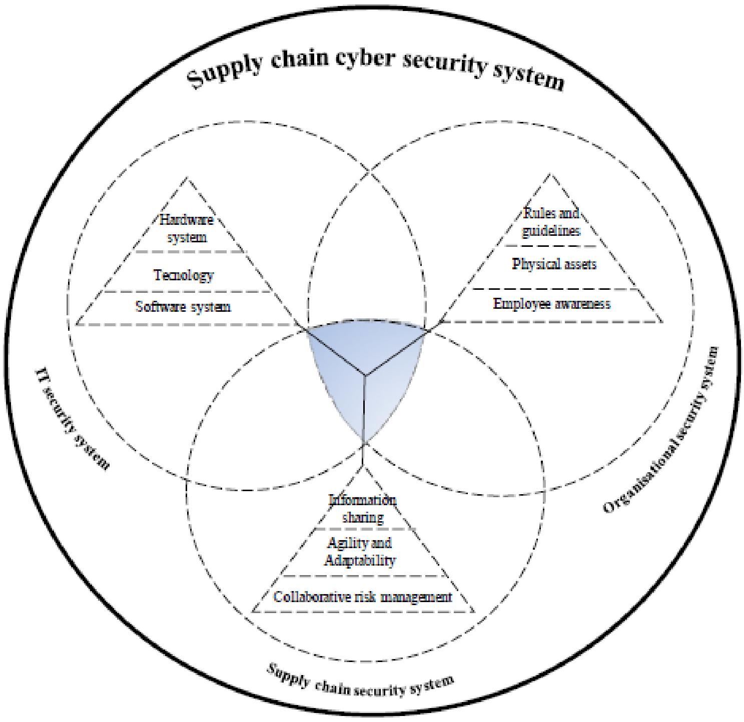

Figure 24: A conceptual model for Supply Chain Cyber Security System[177]

The importance of the alignment of the systems requires furthermore an efficient coordination, collaboration and practice of information sharing within an organization. The authors recommend the coordination of these security systems in order to “standardize and implement agreed cyber security strategies for supply chains and wider networks”[178] due to the fact that the integration of supply chains and digitization, in particular of operational technologies, goes hand in hand. Additionally, Gadghe et. Al. detected a weak spot in the human/behavioral element within the research. Due to a perceived biased towards technical risks such as the hard- and software system, behavioral risks have been less analyzed in the literature. This is one of their located research gaps in the field.

Additionally, they found a lack of empirical testing of specific mitigation measures and their impact on the risk level. This would involve the identification and separation of strategies in pre-, trans-, and post-attack periods and research on when and where these response work best. Furthermore, further large-scale data-driven research is necessary. Overall,

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[177] Ibid., p. 34.
[178] Ibid., p. 35.

they conclude that the area of supply chain cyber security and resilience deserves more attention by diverse research fields.

Resilience Measures & Best Practices

Assessing and understanding supply chain security is a crucial part in order to be able to implement appropriate measures and build trust. A rethinking is needed in which security measures, and in particular cybersecurity, should not be understood as an actual state but as a process that adapts to the constantly changing environment. To this end, traditional approaches to risk mitigation must also be refined to solutions that are more resilient.

The manufacture and distribution of components and products requires a well-coordinated supply chain that receives raw materials for production at the right time and in the right quantity and quality, and delivers the finished products to the end user on demand[179]. Efficient and cost-effective processes require precise coordination of e.g. organizational and technical workflows that are integrated into cyber-physical networks where services, products and information are moved and exchanged. Organizations build or join supply chains according to their needs and business model, with a focus on cost reduction. Not only digital but also physical risks such as earthquakes, floods, fires, pandemics and epidemics have repeatedly proven that the failure of individual components has negative consequences for the entire supply chain due to both physical and digital dependencies. Strategies are therefore essential to manage risks and build-up resilience to ensure business continuity, delivery reliability and responsiveness in line with the following approaches[180]:

- Diversification of suppliers
- Information sharing about risks and challenges
- Stock management
- Building redundancies
- Monitoring traffic

According to McKinsey, a rational starting point is to categorize risks into two clusters: known risks and unknown risks[181]. For known risks, companies should follow the following four steps:

First, already identified risks are catalogued and then mapped according to possible supply chain nodes. Supply chain nodes include suppliers, warehouses and even transport routes. Subsequently, companies should identify and continuously monitor risks[182]. Identified and known risks can thus be measured for statistical analysis and rendered more manageable. For instance, cybersecurity vulnerabilities can be quantified by an analysis of known threat vectors based on existing threat landscapes, followed by initiating the necessary steps as recommended by CERT operations teams or cybersecurity agencies.

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[179] Urciuoli, L., “Cyber-Resilience: A Strategic Approach for Supply Chain Management”, *Technology Innovation Management Review*, 2015, Vol. 5 No. 4, pp 13-18.
[180] Ibid.
[181] T. Bailey, E. Barriball, A. Dey and A. Sankur, “A Practical Approach to Supply-chain Risk Management”, Report, McKinsey, 2019.
[182] Ibid.

The second step is essential as it involves the establishment of a framework for risk management in the supply chain. Three basic questions are to be answered: What happens to the organization when the risk occurs? What are the probabilities of the risk? How well prepared is the organization to deal with that risk? Accordingly, risk management encompasses risk impact, risk probability as well as a general and specific readiness analysis. McKinsey (2019) recommends that companies should follow a scoring methodology in order to prioritize and aggregate across a variety of threats, products and value chains.

Thirdly, McKinsey (2019) recommends persistent risk monitoring. Structural and operational risk drivers should be taken into account. Early warning systems can help to mitigate risks and impacts at this point.

The fourth step requires the introduction of a governance system that regularly reviews the risk management process. The risk board can issue strategic orders that mitigate risks by e.g. altering supply chains or improving overall resilience by introducing agile supply chains. Furthermore, McKinsey (2019) recommends defining transparent responsibilities. For each value chain there should be one representative responsible for the execution of mitigation measures.

For unknown risks, the approach is different since unknown risks are not quantifiable. Unknown risks may relate to cyber incidents such as the so-called Cyber 9/11 or to a cyber vulnerability that is deeply hidden in the IT architecture. First, organizations should build strong defenses to mitigate the overall risks. Strong defenses, from request-for-proposal (RFP) language to employee training, all contribute to an organization identifying and mitigating unknown risks before they affect operations. The second step involves building a “risk-aware culture”[183]. Organizations are just as strong as their weakest link. The establishment of defense layers demands attentiveness and responsibility. Additionally, organizations should aim to minimize response times and avoid chaos. Risk-aware cultures pursue these goals and build on four pillars: A certain degree of bad news tolerance at all levels of the organization allows for swifter solutions. Risk tolerance should be openly communicated so that the organization is fully aligned in the risk mitigation process. Responsibilities should be clearly defined so that employees can react quickly to risks. McKinsey (2019) recommends the creation of a self-responsible environment which enables members to consider themselves responsible for the outcome of actions and decisions.

A complementary risk management framework can be integrated by following the guidelines of the National Institute of Standards and Technology (NIST) from the U.S. Department of Commerce (2020)[184]. This framework is in fact based on the CSCRM model as described above. The best practices can be summarized as follows:

First, it is necessary to recognize that cyber supply chain management is a cross-cutting task as it involves many different layers and nodes of the organization. As a direct

[183] Ibid.
[184] J. Boyens, C. Paulsen, N. Bartol, K. Winkler and J. Gimbi, ”Key Practices in Cyber Supply Chain Risk Management: Observations from Industry”, Report, National Institute of Standards and Technology, 2020, [Online], Available: https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.02042020-1.pdf [Accessed 22 04.2020].

consequence, collaboration across networks is becoming crucial for effectively managing cyber risks. Organizations can implement a centralized cyber supply chain team or a globally dispersed team of supply chain managers working closely with information security officers. Both approaches have advantages and disadvantages in terms of costs, oversight and communication. A blended approach is also possible. Ultimately, this organizational element should be adjusted to the specific corporate culture.

Second, a standardized NIST framework allows companies to speak the same language in terms of risk management, resulting in lower information costs. Standards, best-practices and regulatory demands should all be taken into account to provide a cyber supply chain framework that includes a common risk reaction playbook, standardized incident response, cyber technology and a general cyber policy goal that requires joint action by different organizational levels and third parties.

Furthermore, cyber supply chain management should involve C-level leadership, signaling internal and external importance and risk awareness. Regular risk reporting, governance and the implementation of a risk-aware culture require the involvement of the C-Level.

Fourth, cyber supply chain management ensures the proper delivery of products and services and is therefore critical for minimizing operational disruptions. Hence, cyber supply chain management touches upon critical business goals such as customer satisfaction, brand reputation, business continuity, accounting and reporting process as well as compliance with regulatory demands. Therefore, cyber supply chain management is a critical factor to the functioning of markets.

3.2. Modelling Tools

In this chapter two examples of software tools to model business ecosystems are shortly described. It has to be noted that for business development purposes the modelling can be done at wide variety of levels, from conceptual drafting of e.g. strategic choices to detailed models of specific business transactions. The ecosystem perspective in CyberFactory#1 is focusing more to gaining understanding of the changes in business ecosystems of Factories of Future, which means that the modelling tasks take the more conceptual approach as well. For this kind of conceptual modelling also the common office software tools such as Microsoft powerpoint and Excel could be fully adequate.

3.2.1. TR3DENT Transformation Accelerator

This software is promoted to be especially developed for digital ecosystem modelling purposes. Tr3dent's approach to modelling identifies the following different types of relationships or interactions within the ecosystem (https://www.tr3dent.com/):

- **Products/Services**: The transfer of products or services between stakeholders
- **Value:** Contains those interactions that generate value. In many cases they are considered to be financial but also other forms of value such as likes or reviews are identified.
- **Contractual**: This considers if there is a requirement for a contractual relationship to exist between two stakeholders. This could be something as simple as a Terms & Condition's associated with a booking or an End User Licence Agreement
- **Operational**: This considers what relationships or interactions are required in order to operate the ecosystem effectively.
- **Data**: This contains the data flows throughout the digital ecosystems, and without it nothing would happen. According to Tr3dent the key to this will be using APIs as the channel between stakeholders to enable the data to flow openly and consistently. APIs also play a key role in reducing barriers for adding new partners and services and thus are a strong enabler for an open ecosystem.

TR3DENT Transformation accelerator features

Following key features are copied from TR3DENT website[185].

Stakeholder mapping

Map stakeholders to associated drivers, value statements, risk and other key elements. Assign stakeholders within business model canvases, ecosystem diagrams and process flows. Use the dynamically created stakeholders map diagram to identify gaps and enhance communication.

[185] https://www.tr3dent.com/features/

Ecosystem modeling

Collaboratively model "As is" and "To be" ecosystems by visually creating the different types of stakeholder interactions (i.e. Product/Services, Financial, Operational, Contractual).

Business modeling

Create business models using a range of different canvases (e.g. Business Model Canvas, Lean Canvas, Platform Canvas, etc…). Assign stakeholders to key elements within the canvas and set user-defined filters to identify gaps and communicate the business model effectively to others.

Capabilities mapping

Capabilities Mapping Explore and tag lists of existing hierarchical data e.g. Smart City Platform Capabilities. Company Specific Business Capabilities, Technical Capabilities, Application Maps, etc. All this data can be imported.

Process mapping

Create Process Flows, Use Case, Customer Journey Map, Swimlane Diagrams, etc and link elements to Stakeholders. Source and insert process elements into your diagrams from industry process frameworks such as the TM Forum eTOM model.

3.2.2. ARIS Express

The ARIS concept (Architecture of Integrated Information Systems) allows to reference the following important business uaspects[186]: organizational units; corporate goals; initial and result events; messages; functions; material output, service output and information services; financial resources; machine resources and computer hardware; application software; human output; process environmental data. In order to reduce complexity, meta-classes with similar semantic interrelationships are grouped into ARIS views[186]. ARIS groups the classes and their relationships into views, which serve the purpose of structuring business process models. These views are described briefly in the following and the figures below shows the structure of these five different views[186] [187].

Function view (how, why): the processes transforming input into output are grouped in a function view. Due to the fact that functions support goals, goals are also allocated to function view. In application software, computer-aided processing rules of a function are defined. Thus, application software is closely aligned with functions, and is also allocated to function view.

Organization view (who, where): the class of organization view creates the hierarchical organization structure. This view is created in order to group responsible entities (department, team, position, person, role) or devices executing the same work object.

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[186] Kozina, M.. Evaluation of Aris and Zachman frameworks as enterprise architectures. Journal of information and organizational sciences, Volume 30, Number1 (2006), https://hrcak.srce.hr/20871
[187] https://ariscommunity.com/

Data view (what, when): this view comprises the data processing environment as well as the messages triggering functions or being triggered by functions.

Output view (what): output view contains all physical and non-physical input and output, including funds flows.

Aris process view (what, how, were, who, when, why): relationships among the all views, as well as the entire business process, are modelled and documented in this view.

ARIS business process meta-model

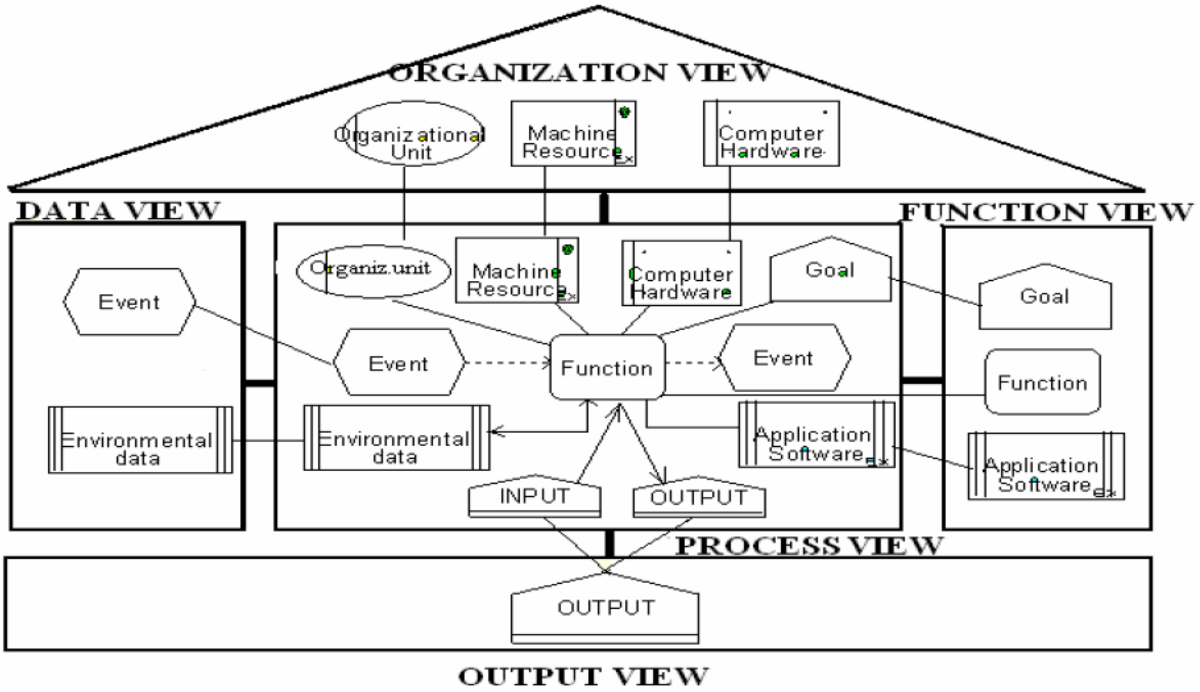

Figure 25: ARIS business process meta-model[188].

3.3. Ecosystem Modelling - Summary

Business ecosystems cover a broad scope of activities and perspectives. Thus there are also broad range of analyses approach on them. However, there are some common aspects in these analyses. From organization viewpoint the approaches answer question such as who are the key actors in the ecosystem, what resources they bring with them and what are their subjective goals and incentives to participate to the ecosystem. From business process perspective the different approaches model the connections between the actors, i.e. what are the events triggering actions between actors, and how do the work-flows, material flows, and value flows go between the partners. The level of detail of modelling depends on what kind of analyses purposes they are made for. Here the levels of strategic, value and technology have been identified, from the more broad level of analysis to more detailed considerations, respectively. They can be linked to the organization-process views so that the strategic level considers matters in more from the organization perspective while value level consideration investigates the business

[188] Kozina, M.. Evaluation of Aris and Zachman frameworks as enterprise architectures. Journal of information and organizational sciences, Volume 30, Number1 (2006), https://hrcak.srce.hr/20871

processes and technology level takes the analyses to the most detailed technical solutions.

Considering the variety of perspectives and potential levels of analysis on the business ecosystems, it is challenging to identify very specific needs to develop modelling approaches or tools. Going to more detailed level of analysis and aiming for example to economic simulation models brings up one fundamental challenge. As the partners in the ecosystem are autonomous business actors they are not so eager to share detailed economic data. They may consider sharing the cybersecurity related data in a similar way. To conclude, the scope and detail of modelling the operation of an ecosystem depends on the specific situation and characteristics of the ecosystem in question.

4. Human Behavior Modelling

Humans will continue to be the focal point of the FoF. However, digitization and more recent advances in machine learning (ML) are said to be the cause of a large transformation of work and economy in most sectors[189] (Brynjolfsson E. a., 2017). This will also change human behavior within the factory ecosystem. Therefore, for a realistic Factory SoS, human factors and human behavior has to be taken into account. This chapter discusses the state-of-the-art of human behavior modeling for the CF#1 SoS from three different perspectives: An experimental economic one, a cybersecurity one, and a human cognitive behavioral one. The following contributions give an overview of the models in the given disciplines. The chapter concludes with a brief summary of identified gaps and limitations in the respective research areas for the task capability of human behavior modelling for the scope of CF#1.

4.1. The Human Profile of the Factory of the Future

In this section, we are interested in the behavior of the humans in the factory of the future. We propose an approach that builds on socio-psychology and experimental economics. While we are well aware of other models of human behavior that seek to understand how individuals and collectives physically act (e.g. Human Movement Simulation – see: MOSIM[190]). However, in the specific circumstances of this task, we are not convinced that this approach is optimal. First is that findings from such analyses might be a foregone conclusion, given the stimulus (a move towards mechanization) that we seek to understand. One would expect physical movement to differ across jobs in any given factory, and thus, if the jobs change, one would expect changes to follow. Rather, attitudes and associated behaviors are more likely to change in the situation we wish to understand.

Second, the presence of the researchers in a partner factory would almost certainly not be unnoticed by the shop floor workers. In turn, as the workers are aware they are being observed, a "Hawthorne effect" would be a valid interpretation of any differences we find. That is, there is some potential that the employees under study could modify their behavior precisely because they are being observed. Due to these concerns, we focus instead of aspects of workers attitudes that cannot be so directly observed, such as trust and cooperation between workers and between workers and management. For example, how might this relationship change, if human managers make use of systems of algorithmic management[191]? Or, how theories of E- leadership postulate, a vision of an IT gradually substituting human management to produce change in organizations[192].

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[189] E. Brynjolfsson and T. Mitchell (2017): What can machine learning do? Workforce implications, in: *Science*, Vol. 358, Issue 6370, pp. 1530-1534.
[190] For more information on the project, see MOSIM – End-to-end Digital Integration based on Modular Simulation of Natural Human Motions: https://mosim.eu/index.html.
[191] M.K. Lee, D. Kusbit, E. Metsky and L. Dabbish (2015): Working with Machines: The Impact of Algorithmic and Data-Driven Management on Human Workers, Conference Paper CHI '15 Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.
[192] B. J. Avolio, S. Kahai and G. E. Dodge (2000): E-Leadership: Implications for Theory, Research, and Practice, in: Leadership Quarterly, Vol. 11(4), pp- 615–668.

A noticeable trend in the labor markets of developing countries is the increasing polarization in job quality[193]. Polarization theory posits that the quality of jobs available in advanced economies becomes increasingly bimodal. At one end are high-skilled professions that require advanced education. These jobs are typically "good", in both the domains of the standard labor supply model[194] and in wider considerations of job quality[195]. Under the Clark model, these jobs are those that pay well, do not demand excessive hours worked and are secure. In addition, they are jobs where the work is interesting and where workers have a high degree of autonomy. Beyond Clark, other domains might become important, such as the duration of the commute, the physical safety of the workplace and the formality of the contract. At the other are jobs that are considered "bad", which are, essentially, jobs that do not exhibit any of the above.

Two main theories are proffered to explain this "missing middle"[196]. The first explanatory framework focuses on a process by which mid-level skilled jobs are displaced to other parts of the world, where labor is cheaper[197]. The second one concentrates on increased mechanization, by which routine skilled tasks are replaced by machines[198]. Some jobs are difficult to "export" or mechanize, such as janitorial work but this is not true for semi-skilled and skilled work that relies on routine tasks. These tasks can easily be mechanized, while integrated transport systems allows them to take place anywhere in the world. Higher quality jobs, which requite high levels of skill and education, will tend to cluster in the economic and geographic spaces that provide those workers in sufficient numbers.

At the human level, a number of key reflections stem from these observations. First, there is a strong relationship between job quality and welfare[199]. For example, those with higher

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[193] S. Houseman, "Job Growth and the Quality of Jobs in the U.S. Economy", *Labour* (1995 Special Edition), 1995, pp. 93-124; M. Goos and A.Manning, "McJobs and MacJobs: the Growing Polarisation of Jobs in the UK", in: *The Labour Market under New Labour*, Palgrave Macmillan, London, pp. 70-85; C. Holmes, "Job Polarisation in the UK: An Assessment Using Longitudinal Data, SKOPE Research Paper 90, University of Oxford, Oxford, 2010.
[194] The standard model of labour market supply defines utility as a trade-off between consumption and leisure time, such that: $U_i = f(C_i, L_i)$. Thus, the decision of how much to work boils down to relatively preferences over income (which drives consumption) and leisure time (which is enjoyable but comes at the cost of foregone consumption).
[195] A. Clark, "Your Money or Your Life: Changing Job Quality in OECD Countries", *British Journal of Industrial Relations*, 43 (03), 2005, pp. 377-400; A. Clarke, "Work, Jobs and Wellbeing Across the Millennium", in: E. Diener, J. Helliwell and D. Kahneman (Eds.), *"International Differences in Well-Being"*, Oxford University Press, Oxford, 2010, pp. 436-468.
[196] C. Wallace, F. Pichler and B. Hayes, *First European Quality of Life Survey: Quality of Work and Life Satisfaction*, 2007, [Online], Available: https://www.eurofound.europa.eu/publications/report/2007/quality-of-life/first-european-quality-of-life-survey-quality-of-work-and-life-satisfaction [Last Accessed 23 04 2020]; J. Leschke, A. Watt and M. Finn, "Putting a Number on Job Quality: Constructing a European Job Quality Index" (No. ETUI-REHS Working Paper No. 03), 2008; C. García-Pérez, M. Prieto-Alaiz and H. Simón, "A New Multidimensional Approach to Measuring Precarious Employment", *Social Indicators Research*, Vol. 134 No. 2, 2017, pp. 437-454.
[197] E. Schokkaert, E. Verhofstadt and L. Van. Ootegem, "Measuring Job Quality and Job Satisfaction", *Working Papers of Faculty of Economics and Business Administration*, Ghent University, Ghent, 2009.
[198] D. Autor, "Why Are There Still So Many Jobs? The History and Future of Workplace Automation", *Journal of Economic Perspectives*, Vol. 29 No. 3, 2015, pp. 3-30.
[199] F. Green, *Demanding Work: The Paradox of Job Quality in the Affluent Economy*, Princeton University Press, Princeton, 2007; D. Gallie, *Employment Regimes and the Quality of Work*,

quality jobs tend to report greater satisfaction with their own lives when asked and score higher on other measures of welfare, such as optimism about the future. Second, there are strong relationships between job satisfaction (which proxies job quality[200]) and behavior[201], both on and off the job[202]. For example, workers who are less satisfied with their jobs have higher rates of absenteeism, are more likely to have long-term health problems and tend to be less productive. Third, there are strong relationships between job quality and attitudes and emotions[203]. This can include low motivation and worsened mental health, which of course is then likely to interact with the issues raised under the previous point.

As with the factory of today, humans will play a role in the factory of the future. However, as the factory of today moves towards becoming the factory of the future, the profile of workers in that factory – particularly on the shop floor – will change. And with those changes, likely also the quality of jobs, with associated impacts on motivation, attitudes, beliefs and the nature of inter-personal interactions. Indeed, during and after the transition phase, it is likely that a number of sub-transitions will take place. Some workers might lose their jobs altogether. Others might experience improvements in job quality. Others might experience worsening of their job quality. In the factory – as with in economies as a whole – there might be a polarization of jobs between highly skilled and lowly skilled positions (and, thus, between "good" and "bad" jobs). All of this is likely to impact on the attitudes workers have towards work, towards management and towards each other, which could

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Oxford University Press, Oxford, 2009; S. Drobnič, B. Beham and P. Präg, "Good Job, Good Life? Working Conditions and Quality of Life in Europe", *Social Indicators Research*, Vol. 99 No. 2, 2010, pp. 205-225; M. S. Gómez-Salcedo, L. A. Galvis-Aponte and V. Royuela, V., "Quality of Work Life in Colombia: A Multidimensional Fuzzy Indicator", *Social Indicators Research*, Vol. 130 No. 3, 2017, pp. 911-936; D. Esenaliev, and N. T. Ferguson, "The Impact of Job Quality on Wellbeing: Evidence from Kyrgyzstan" *Social Indicators Research*, Vol. 144 No. 1, 2019, pp. 337-378.

[200] J. A. Ritter and R. Anker, "Good jobs, Bad jobs: Workers' Evaluations in Five Countries", *International Labour Review*, Vol. 141 No. 4, 2002, pp. 331-358; G. Green and S. A. Reese, "Job Satisfaction among High School Athletic Administrators", *Education*, Vol. 127 No. 2, 2006, pp. 318-321.

[201] D. C. Thomas and K. Au, "The Eeffect of Cultural Differences on Behavioral Responses to Low Job Satisfaction", *Journal of International Business Studies*, Vol. 33 No. 2, 2002, pp. 309-326.

[202] D. Farrell, "Exit, Voice, Loyalty, and Neglect as Responses to Job Dissatisfaction: A Multidimensional Scaling Study" *Academy of Management Journal*, Vol. 26 No. 4, 1983, pp. 596-607; T. M. Probst and T. L. Brubaker, The Effects of Job Insecurity on Employee Safety Outcomes: Cross-sectional and Longitudinal Explorations", *Journal of Occupational Health Psychology*, Vol. 6 No. 2, 2001, 139-159; W. E. Hoogendoorn, P. M. Bongers, H. C. W. De Vet, G. A. M. Ariens, W. Van Mechelen and L. M. Bouter, "High Physical Work Load and Low Job Satisfaction Increase the Risk of Sickness Absence due to Low Back Pain: Results of a Prospective Cohort Study", *Occupational and Environmental Medicine*, Vol. 59 No. 5, 2002, pp. 323-328; J. Barling, E. K. Kelloway and R. D. Iverson, "Accidental Outcomes: Attitudinal Consequences of Workplace Injuries", *Journal of Occupational Health Psychology*, Vol. 8 No. 1, 2003 74-85.

[203] D. Gallie, A. Felstead and F. Green, (2012). "Job Preferences and the Intrinsic Quality of Work: The Changing Attitudes of British Employees 1992-2006", *Work, Employment and Society*, Vol. 26 No. 5, 2012, pp. 806-821; M. L. Usdansky, R A. Gordon, X. Wang and A. Gluzman, "Depression Risk among Mothers of Young Children: The Role of Employment Preferences, Labor Force Status and Job Quality" *Journal of Family and Economic Issues*, Vol. 33 No. 1, 2012, pp. 83-94.

affect productivity and interrupt the other processes put in place within the factory. And all of this is before we consider the potential impacts of cognitive dissonance[204].

While the management of humans in the factory of the future is the focus of a long line of research[205], the profiles of those workers, or the relationship between these profiles and the work those workers do (and how this is influenced by transitions towards more advanced factory floors) remains under-researched. Yet, in many ways, the transition of a single factory mimics the transition of entire sectors or markets. Understanding the profile, preferences, behaviors and attitudes of workers in the factory of the future, and how they differ from those of workers in the factory of today, is at the core of this module.

4.2. Econometric Modelling Approaches

4.2.1. Paper-Based Survey for Data Collection

We will rely on closed-form survey data, collected from shop floor workers in a facility that is about to undergo transition. The use of such a data collection approach allows ready conversion of the answers into quantitative data (e.g. ordinal and dummy variables), which in turn facilitates the use of statistically modelling techniques. This approach places the individual as the unit of analysis (rather than, say, a country, region, or firm). This provides the opportunity to understand the transitions that individuals experience, and what determines these transitions. Within the limitations of this study, factors such as statistical power also become relevant. It is unlikely, for example, that enough factories are available for analysis to draw accurate statistical inference from analyses focusing on this unit of analysis. The use of statistical methods allows us to develop a “counterfactual” based analysis, that not only seeks to understand the changes that have taken place but to understand the impact of those changes, vis-à-vis a situation where they did not occur.

4.2.2. Data Collection Approach

Prior experience suggests that paper-based surveys will allow us to collect data in the most efficient way possible. This approach allows us to conduct surveys with multiple individuals concurrently – for example, during breaks – that would not be possible with tablets or computers, due to the availability, only, of a relatively small number of devices. Paper-based data will be digitized by research assistants and coded for use in statistical software packages. This data will be made available to project partners on request. Surveys will be printed and brought to the factory during the data collection phase, if the global healthcare situation allows. If not, they will be sent to factory managers to be printed and distributed, thus allowing for remote collection of the data.

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[204] F. M. Andrews and A. C. McKennell, “Measures of Self-reported Well-being: Their Affective, Cognitive, and Other Components”, *Social Indicators Research*, Vol. 8 No. 2, 1980, pp. 127-155; W. Pavot, W. and E. Diener, “The Affective and Cognitive Context of Self-reported Measures of Subjective Well-being”, *Social Indicators Research*, Vol. 28 No. 1, 1993, pp. 1-20.

[205] H. Thompson and R. Scalpone, R. “Managing the Human Resource in the Factory of the Future”, *Human Systems Management*, Vol. 5 No. 3, 1985, pp. 221-230; A. McKinlay and P. Taylor, *Foucault, Governmentality, and Organization: Inside the Factory of the Future*, Routledge, Abingdon, 2014.

4.2.3. Data Collection Analysis

We will use advanced econometric techniques in order to analyze the data. Depending on the precise configuration of the data available and the research question at hand, a number of methods are available. **Our aim is to choose a statistical methodology that minimizes statistical bias and produces the most efficient results.** We note, however, that there is no "hierarchy" of methods, where the suitability of one approach is strictly superior to another. Rather, the most appropriate method is a result of the circumstances in which the analysis takes place. In this sense, in this section, we rather consider some of the problems that our data collection will face and the standard statistical solutions to these problems.

In standard statistical analyses, **ordinary least squares (OLS)** is often used as the best linear unbiased starting place[206]. This is a statistical approach that allows the identification of correlations between key variables, by holding all other intervening variables constant. It works by minimizing the sum of the differences between the observed values of the dependent variable and those predicted. If specific assumptions hold, OLS will identify a causal relationship between two variables. However, the approach imposes stringent, and often unrealistic, assumptions on the model and is easily biased by (for example) omitted variables. This occurs, for example, when we seek to correlate two variables of interest that are related to a third variable that is not included in the model. For example, should one wish to understand the determinants of income, one might include both a person's education level and his or her experience. However, both education and experience are likely to be correlated, also, with that person's "talent", which is not observed and, therefore, not included in the model. In this situation, this would lead us to overestimate the importance of education and experience. In other cases, however, the effects could be even more pernicious – suggesting a relationship that does not exist at all.

Due to our survey and experimental setup, it is likely that we will overcome these standard forms of bias. However, in the event that biases appear to be evident, we will rely on an **instrumental variables approach**[207]. This approach works on the principle of replacing so-called "endogenous variables" (that is, variables that are correlated with other aspects of the model) with "instruments" that are not correlated with other aspects of the model, but which are correlated with the endogenous variable.

However, this design does introduce other potential concerns. For example, we are interested in the evolution in job quality and attitudes of individuals as the factory changes. Our priors suggest that some people we interview during the first phase (baseline) will not be present in the survey at endline. However, this poses a selection problem[208]. That is, the determinants of why some people remain in the sample, while others are lost, could partly determine the outcomes in which we are interested. For example, those who remain

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[206] F. W. McElroy, "A Necessary and Sufficient Condition that Ordinary Least-squares Estimators Be Best Linear Unbiased", *Journal of the American Statistical Association*, Vol. 62 No. 320, 1967, pp. 1302-1304.
[207] See for an overview: R. J. Bowden and D. A. Turkington, *Instrumental Variables* (Vol. 8). Cambridge University Press, Cambridge, 1990.
[208] C. R. Henderson, C. R., "Best Linear Unbiased Estimation and Prediction under a Selection Model", *Biometrics*, 1975, pp. 423-447.

in the factory might be the most productive, or most highly qualified, individuals and, thus, the group whose job quality might improve, anyway.

To overcome this problem, we will implement a **Heckman selection correction model**. In this approach, one seeks to understand factors that determine selection into the situation, but that otherwise do not influence the outcome under analysis. For example, in an analysis of women's wages, a suitable criterion might be marital status. This could influence the decision to work or not but is unlikely to determine income directly, conditional on the first decision[209]. Due to the relative simplicity of our experimental design and data collection, the easy computation of a standard Heckman model will be sufficient.

We will rely on an **Oaxaca-Blinder decomposition technique** in order to differentiate the observable and unobservable changes in the workforce. The approach works by splitting data into two groups (e.g. men and women) and seeking to explain the gap in outcomes between those two groups. For example, if one is interested in the wage differential, one decomposes the observed gap into two components: that which is due to the differences in the means of a variable of interest between the groups (e.g. education or experience); and that which looks at the difference of the impact of the variable on the outcome across the groups. That is, some of the wage differential is explained (e.g. by men and women having different characteristics) some of it us "unexplained" (e.g. by men and women receiving differing rewards for having the same characteristics)[210].

Broadly speaking, these criticisms fall into those that relate to the specification of the model; and those that stem from the underlying data. Careful model specification and sensitivity analyses will be used to minimize the former. The latter require more thought and are subject to more specific criticisms[211] (Atal et al., 2009). Particularly, that the decomposition only gives information about average differences, but omits differences across the distribution of the sample. For example, the extent (and nature) of differences between men's and women's incomes might be different for those in the bottom decile of the distribution than in the highest; and, indeed, the bottom 10% of the male distribution might not have the same parameters as the women's distribution. In a similar way, it does not necessarily compare similar individuals.
Given the likely close clustering of the outcomes in which we are interested and the likely similarity in the profiles of shop floor workers, these concerns are unlikely to arise. In this sense, we rely on the more intuitive Oaxaca-Blinder decomposition than its more advanced alternatives. Other advanced techniques will be used as and when the need arises. This can only be confirmed with inspection of the data, once it has been collected.

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[209] An overview of this model and its critiques can be found in: P. Puhani, "The Heckman Correction for Sample Selection and Its Critique", *Journal of Economic Surveys*, Vol. 14 No. 1, 2000, pp. 53-68.
[210] A review of this approach and its limitations can be found in: C. G. Ospino, P. R. Vasquez and N. B. Narváez, "Oaxaca-Blinder Wage Decomposition: Methods, Critiques and Applications: A Literature Review", *Revista de Economía del Caribe*, No. 5, 2010, pp.237-274.
[211] J. P. Atal, H. Ñupo and N. Winder, "New Century, Old Disparities: Gender and Ethnic Wage Gaps in Latin America" *IDB Working Paper Series No. IDB-WP-109*, Inter-American Development Bank, 2009.

Drafts of the survey and experimental questionnaires are included in this document as an Annex.

4.3. Human Factors in Cybersecurity

Humans have a critical role in cybersecurity, as common threats to organisations include actions conducted by internal or external threat actors. The term "threat actor" is an ambiguation that refers to a person or group that includes (1) organized crime, (2) advanced persistent threats, (3) insider threats, (4) hacktivists and (5) other malcontents[212]. The type of threat actor involved in a cybersecurity event defines their capabilities and motives. Stillions (2014) describes a model of cyber threat intelligence, the detection maturity level (DML), that describes an organizations ability to detect cyber attacks[213]. The model, shown below, traverses across technical aspects of a cyberattack (indicators, network artifacts) to more human aspects (goals, strategy).

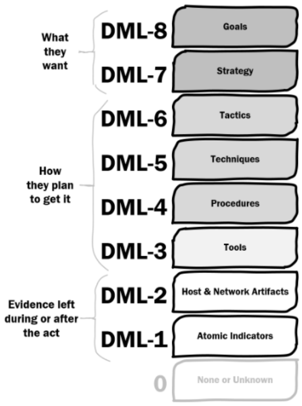

Figure 26: Ryan Stillions' (2014) DML[214]

Mavroeidis and Bromander (2017) provide a review of cyber threat taxonomies and ontologies, including the DML model, and suggest that the model could be improved by including aspects of threat actor motivation and identity[215]. Comprehensive cyber defense, suggested by Mavroeidis and Bromander (2017), is complicated by a lack of cohesiveness among taxonomies and ontologies. Improving the quality of information in accordance with their proposed threat intelligence model, shown below, will allow for a more advanced detective and preventive defenses[216]. The factors related to humans, their identity and motivations, will be explored.

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[212] "Threat Actor Basics: Understanding the 5 Main Threat Types", SentinelOne, [Online], Available: https://www.sentinelone.com/blog/threat-actor-basics-understanding-5-main-threat-types/. [Accessed 19 04 2020].
[213] R. Stillions, "The DML Model", [Online], Available: http://ryanstillions.blogspot.com/2014/04/the-dml-model 21.html. [Accessed 19 04 2020].
[214] Ibid.
[215] V. Mavroeidis and S. Bromander, "Cyber Threat Intelligence Model: An Evaluation of Taxonomies, Sharing Standards, and Ontologies within Cyber Threat Intelligence", in: *2017 European Intelligence and Security Informatics Conference (EISIC)*, IEEE, 2017, pp. 91-98.
[216] Ibid.

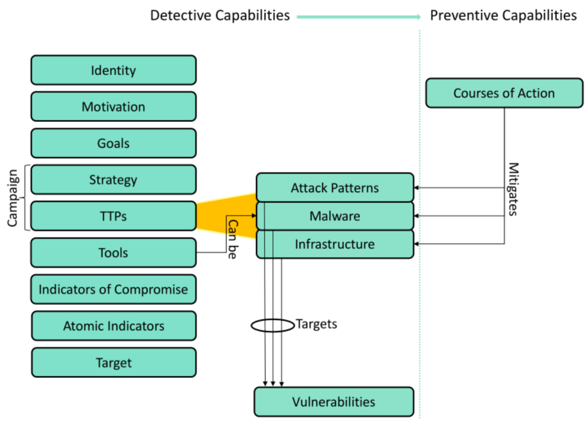

Figure 27: Cyber Threat Intelligence Model, from Mavroeidis and Bromander (2017)[217]

Evans et al. (2016) provide a review of cybersecurity assurance processes, with a focus on human behaviour impacts[218]. They show that, as of 2015, half of all security incidents are attributable to one common element: people and their mistakes. Statistic quality control in services has not kept up with manufacturing due to difficulty of quantifying vulnerabilities in human behaviour[219]. The authors review survey data showing that information that is not easily quantifiable is ineffective as management information hinders cybersecurity planning. An extension of this observation is that adopting methods that quantify human behaviour will improve decision-making capabilities with respect to cybersecurity.

4.3.1. Modeling Human Behaviour in Cyberfactory #1

To bridge the shortcoming of cybersecurity considerations for human behaviour, Evans *et al.* (2016) argue that human reliability analysis (HRA) methods from the industries of petro-chemical, nuclear and aviation can be borrowed, and the authors stress the significance of this area of analysis[220]. HRA is a retrospective or predictive analysis method to determine the ability of a human to perform a particular task at a given time and conditions[221]. Techniques and models for conducting HRA include HEART, THERP, HCR, STAHR and ATHENA. Prevalent HRA techniques will be discussed in the following section.

Cybersecurity events stemming from human behaviour extends beyond errors and mistakes and includes intentional acts of malicious behaviour. From Nurse *et al.* (2014), there are two categories of cybersecurity events caused by insiders: (1) unintentional harm caused by accidental or erroneous behaviour, as previously mentioned and addressed with

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[217] Ibid.
[218] M. Evans, L. A. Maglaras, Y. He and H. Janicke, "Human Behaviour as an Aspect of Cybersecurity Assurance", *Security and Communication Networks*, Vol. 9 No. 17, 2016, pp. 4667-4679.
[219] Ibid.
[220] Ibid.
[221] T. Gu, L. Li, M. Lu and J. Li, "Research on the Calculation Method of Information Security Risk Assessment considering Human Reliability", in: *2014 10th International Conference on Reliability, Maintainability and Safety (ICRMS)*, IEEE, 2014, pp. 457-462.

HRA, and (2) intentionally malicious activity[222]. A framework for understanding insider behaviour is proposed by Nurse *et al.*, which includes consideration for a catalyzing event, actor characteris, attack characteristics and organization characteristics[223]. Frameworks and models that describe insider threats will be reviewed.

4.3.1.1. Human Reliability

The purpose of HRA is to predict whether an operator will perform an action incorrectly. Di Pasquale *et al.* (2013) review HRA techniques applicable to manufacturing operations, and define three categories, or generations, of frameworks: (1) quantitative, (2) qualitative and (3) dynamic[224]. Different techniques apply in differing contexts with the common goal of predicting the likelihood of an error with given factors. Di Pasquale *et al.* further propose a simulation module for evaluating human reliability with two goals: (1) Prevention via analysis of potential scenarios, and (2) Post-production evaluation of influencing factors.[225] Conducting HRA typically involves quantification of a human's error probability (HEP) with the use of error-influencing factors, or performance-shaping factors (PSF), which can be environmental, personal or contextual. While PSFs are numerical, HRA involves aspects of dynamic human behaviour, including psychological, cognitive and physical attributes, which are more difficult to quantify.

The first generation of HRA techniques include the Technique for Human Error Rate Prediction (THERP), Accident Square Evaluation Program (ASEP), Human Error Assessment and Reduction Technique (HEART), and others. Of these techniques, THERP is referenced as the most popular and effective.[226] Primarily developed by A. D. Swain (1964), THERP is described as an iterative process with five steps[227]:

- Define the system or subsystem to evaluate
- List and correlate all required human operations with system functions
- Attach an error rate to each human operation or group of operations
- Evaluate the effect of human errors on the system
- Redesign operations or functions to reduce error, as necessary

Swain (1964) outlines how event (in)dependence, stress, climate, motivation, and other factors are accounted for in the model via the assembly of a probability tree. This tree has actions as nodes and failure or success as branches, where each branch is assigned a probability. Leafs of the tree are outcomes, which can be overall success or failure. A sample probability tree from Swain (1964) is shown below.

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222 J. RC Nurse, O. Buckley, P. A. Legg, M. Goldsmith, S. Creese, G. RT Wright and M. Whitty, "Understanding Insider Threat: A Framework for Characterising Attacks"; in: *2014 IEEE Security and Privacy Workshops*, IEEE, 2014, pp. 214-228.
223 Ibid.
224 V. Di Pasquale, R. Iannone, S. Miranda and S. Riemma, "An Overview of Human Reliability Analysis Techniques in Manufacturing Operations", *Operations Management*, 2013, pp. 221-240.
225 Ibid.
226 Ibid.
227 A. D. Swain, THERP. No. SC-R-64-1338. Sandia Corp., Albuquerque, N. Mex., 1964.

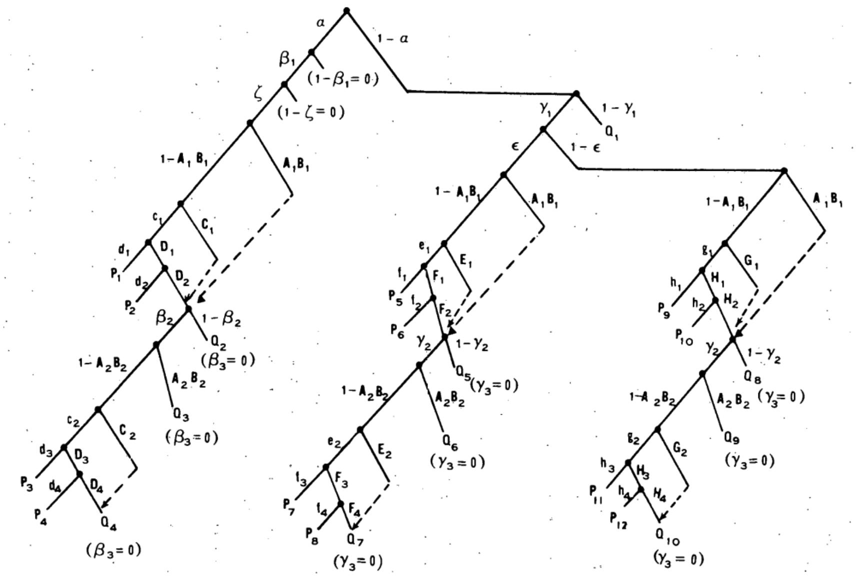

Figure 28: THERP Probability Tree with Successes (P) and Failures (Q), from Swain (1964)[228]

THERP and other first-generation HRA techniques share the following characteristics:

- Binary outcomes of success or failure
- Phenomology of human action
- Human cognition and context are not directly addressed
- Emphasise quantifying failure
- Separation of errors of omission from errors of comission

Di Pasquale *et al.* (2013) highlights the shortcomings of THERP and similar methods, suggesting that it is not enough to quantify an error probability without understanding causes, which stem from cognition factors, the environment, organisational influences or other PSFs[229]. Nonetheless, THERP is widely used due to ease of implementation and effectiveness.

Another popular first-generation method, the Human Error Assessment and Reduction Technique (HEART), is intended to provide a simple approach to performing HRA[230]. The approach to conduct HRA with HEART is simple: The technique provides a list of tasks with base HEP values (along with 5th and 95th percentile bounds) that are multiplied against weighted error-producing conditions (EPCs). A list of EPCs with their maximum contribution are described within the technique. The weight applied to each EPC is based on the judgement of the analyst for a given task.

HEART is a versatile HRA method with wide applicability and has been empirically validated[231]. A few shortcomings should be considered before employing the technique:

[228] Ibid.

[229] V. Di Pasquale, R. Iannone, S. Miranda and S. Riemma, "An Overview of Human Reliability Analysis Techniques in Manufacturing Operations", Operations Management, 2013, pp. 221-240.

[230] J.C. Williams, "HEART - A Proposed Method for Achieving High Reliability in Process Operation by Means of Human Factors Engineering Technology", *Safety and Reliability*, Vol. 35 No. 3, 2015, pp. 5-25.

[231] J. Bell and J. Holroyd, "Review of Human Reliability Assessment Methods", *Health & Safety Laboratory* 78, 2009.

lack of consideration for error dependencies, missing task decomposition guidelines and potential “double-counting” of EPCs with task descriptions[232]. The Nuclear Action Reliability Assessment (NARA), considered a “third-generation” technique builds upon HEART for application within the Nuclear power industry[233]. While not widely applicable, the model does support a notion that task types, their associated nominal HEP values, and EPCs may be extensible to accommodate any shortcoming of the base HEART model.

Second generation techniques attempt to define causal relationships between PSFs and error probabilities. Within this category are techniques such as A Technique for Human Event Analysis (ATHEANA) and the Cognitive Reliability and Error Analysis Method (CREAM). As CREAM has more evidence of use it will be described here.[234]

CREAM helps bridge the gap of causes (genotypes) and manifestations (phenotypes) of errors, combining psychology with HRA[235]. Genotypes are categorized as pertaining to either an individual, the technology they are using or their organisation. There are four groups of phenotypes: actions at the wrong time, actions of the wrong type, actions on the wrong object or actions in the wrong place.

CREAM begins with task analysis, where tasks are described along with common performance conditions (CPC). Hollnagel (1998) lists nine CPCs applicable to tasks within CREAM, along with descriptors indicating their effects on a task[236]:

1. Adequacy of organisation
   - Very efficient; Efficient; Inefficient; Deficient
2. Working conditions
   - Advantageous; Compatible; Incompatible
3. Adequacy of man-machine interface
   - Supportive; Adequate; Tolerable; Inappropriate
4. Availability of procedures and/or plans
   - Appropriate; Acceptable; Inappropriate
5. Number of simultaneous goals
   - Fewer than capacity; Matching capacity; More than capacity
6. Crew collaboration quality
   - Very efficient; Efficient; Inefficient; Deficient
7. Available time
   - Adequate; Temporarily inadequate; Continuously inadequate
8. Time of day
   - Day-time (adjusted); Night-time (unadjusted)
9. Adequacy of training and experience
   - Adequate, high experience; Adequate, limited experience; Inadequate

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[232] Ibid.
[233] J. Bell and J. Holroyd, "Review of Human Reliability Assessment Methods”, Health & Safety Laboratory 78, 2009.
[234] Ibid.
[235] E. Hollnagel, *Cognitive Reliability and Error Analysis Method* (CREAM), Elsevier, 1998.
[236] Ibid.

After determining levels for each CPC, a combined score is calculated as a triplet of the following form: [$\Sigma_{reduced}$, $\Sigma_{insignificant}$, $\Sigma_{improved}$]. The combined score determines control mode, as depicted in the image below[237].

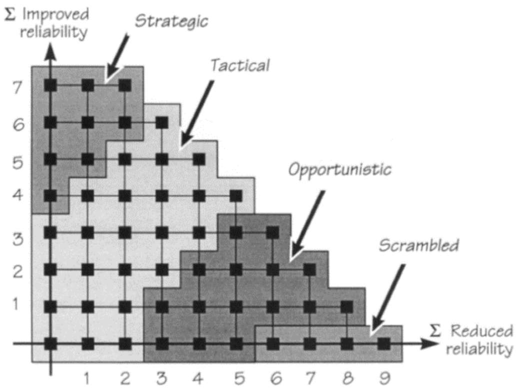

Figure 29: Control Modes, from Hollnagel (1998)[238]

Once a control mode is known, the method provides error probability intervals for a given mode for each task. Tasks with particularly high error probabilities are screened for extended analysis. A summary of CREAM is as follows:

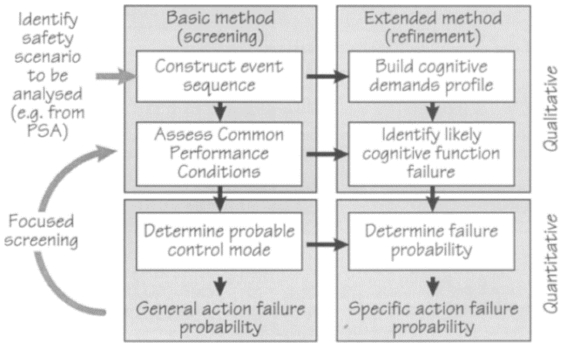

Figure 30: CREAM[239]

The extended method builds on the basic method and is intended to produce specific action failure probabilities with the following steps:

- Build/develop a profile of cognitive demands of each task and map to cognitive functions
    - Cognitive demands are method-defined and include: co-ordinate, communicate, compare, exectute, monitor, ect.
    - Cognitive functions are: observation, interpretation, planning, exectution
- Identify likely failures
    - Each task, as a whole, is assigned a predominant failure mode (or, error mode) based on its cognitive function categorization(s).
- Determine action failure probability
    - Each failure is assigned a nominal cognitive failure probability (CFP)
    - Apply CPC to nominal CFP

[237] Ibid.
[238] Ibid.
[239] Ibid.

- Incorporate adjusted CFP into event tree (by applying a weight factor based on the control mode)

CREAM is a method for performance prediction and provides basic and extended techniques to quantify error probabilities.

To measure the effect of human behaviour on the outcome of a system, including aspects of cybersecurity, we can employ methods, techniques and models from the field of HRA. Numerous techniques exist, including those that extend previous models. With careful selection of task descriptions, HEPs, PSF, EPCs, etc., we can defined a model to predict human behavioural impact on cybersecurity.

4.3.1.2. Malicious Actors and Insider Threats

Apart from making errors during execution of tasks, humans within Cyberfactory#1 may also have malicious intent. Nurse *et al.* (2016) describe the characteristics of insider threats, showing in the image below, to include: psychological state, physical behaviour, cyber behaviour, personality, role, type, relationship, motivation, skill set and opportunity. The authors demonstrate their framework in three scenarios: (1) fraud, (2) accidental leakage and (3) human errors.

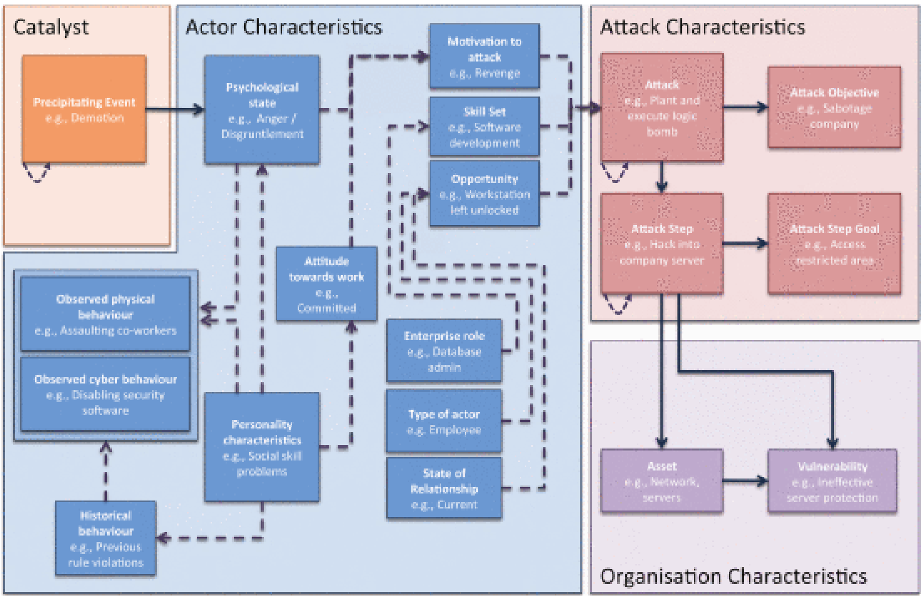

Figure 31: Characterizing insider threats, per Nurse et al. (2016)[240]

This framework provides a valuable means to qualify previous incidents, it is not described nor presented as a descriptive model. For modelling attacks, Kandias *et al*. (2010) propose a technique that considers psychological, user taxonomy and system usage profiling for a

[240] J. RC Nurse, O. Buckley, P. A. Legg, M. Goldsmith, S. Creese, G. RT Wright and M. Whitty, "Understanding Insider Threat: A Framework for Characterising Attacks"; in: 2014 IEEE Security and Privacy Workshops, IEEE, 2014, pp. 214-228.

decision process that determines potential for malicious behaviour[241]. The decision manager assesses behaviour in terms of motive, opportunity and capability.

The approach from Kandias *et al.* (2010) has a focus on individuals and their characteristics. A given user's taxonomy consists of four dimensions: *system role, sophistication, predisposition* and *stress level*. These are measured on a 3-point scale (e.g. low, medium, high). To build a complete user's taxonomy, psychological characteristics of that user are needed to be understood. Psychological profiling pulls from Social Learning Theory and has three stages[242]:

1) User Sophistication, as determined via questionnaire
    - System knowledge; Techniques; Technology familiarity
2) Predisposition, as determined via questionnaire
    - Past delinquent behaviour; Ability to reproduce ideas; Family/friend influences; Differential association; Perception on balance of punishment/rewards; Moral disengagement; Sense of collective responsibility; Victim-blaming
    - End result of questioinnaire is to categorize as "low", "medium" or "high".
3) Stress, as evaluated from psychometric test
    - Result categorized stress as "low", "medium" or "high"

System usage profiling is the last step before the decision manager. Here, the user's real-time behaviour with information systems is monitored. The model is geared toward typical office equipment yet the concepts apply to CyberFactory#1. The three dimensions of usage profiling are: *system call analysis, intrusion detection* and *honeypots*. System call analysis and intrusion detection both refer to determining if a particular behaviour is typical for a user in a certain context. Honeypots are artifacts disguised as targets of opportunity for potential malicious actors, such as a file hosted on a networked device posing as sensitive user information. User interaction with a honeypot is indicative of an insider threat. The image below shows how these three characterizations feed into the decision manager[243].

[241] M. Kandias, A. Mylonas, N. Virvilis, M. Theoharidou and D. Gritzali, "An Insider Threat Prediction Model", *International Conference on Trust, Privacy and Security in Digital Business*, Springer, Berlin, Heidelberg, 2010, pp. 26-37.
[242] Ibid.
[243] Ibid.

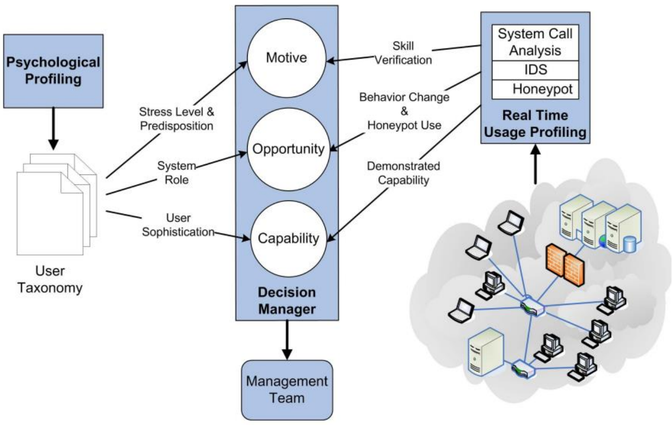

Figure 32: An Insider Threat Prediction Model[244]

The last step, the decision manager, takes input from all characterizations in three factors: Motive, Opportunity and Capability. Motive is determined as a function of predisposition (P), stress (S) and skill verification (V): $\boldsymbol{M} = \boldsymbol{f}(\boldsymbol{P}, \boldsymbol{S}, \boldsymbol{V})$, and sample values are provided by Kandias *et al.* (2010) in the following table.[245]

Skill Verification	Stress Level	Predisposition		
		Low	Medium	High
False	Low	1	2	3
	Medium	2	3	4
	High	3	4	5
True	Low	2	3	4
	Medium	3	4	5
	High	4	5	6

Figure 33: Sample Values for Motive Score, from Kandias et al. (2010)

Opportunity score is derived as a function of behavioural change (B), role (R) and honeypot usage (H): $\boldsymbol{O} = \boldsymbol{f}(\boldsymbol{B}, \boldsymbol{R}, \boldsymbol{H})$**,** with sample values provided.

Behavior Change	Honeypot Use	System Role		
		Novice	Advanced	Administrator
False	False	1	2	3
	True	2	3	4
True	False	3	4	5
	True	4	5	6

Figure 34: Sample Values for Opportunity Score, from Kandias et al. (2010)

The capability score depends demonstrated capability (D) and sophistication (S): $\boldsymbol{C} = \boldsymbol{f}(\boldsymbol{D}, \boldsymbol{S})$ with sample values as provided.

Demonstrated Capability	User Sophistication		
	Low	Medium	High
Low	1	2	3
Medium	2	3	4
High	3	4	5
Very High	4	5	6

Figure 35: Sample Values for Capability Score, from Kandias et al. (2010)

The final threat level is a summation of motive, opportunity and capability $\boldsymbol{T} = \boldsymbol{M} + \boldsymbol{O} + \boldsymbol{C}$. Specifically assigned values for scoring are context-specific and organisations should set

244 Ibid.
245 Ibid.

values relevant to their needs. Sample values for final outcomes are provided by Kandias *et al*. (2010), with higher values indicating an individual's likelihood to exhibit insider threat behaviours.

Motive	Opportunity	Capability		
		Low	Medium	High
Low	Low	3	4	5
	Medium	4	5	6
	High	5	6	7
Medium	Low	4	5	6
	Medium	5	6	7
	High	6	7	8
High	Low	5	6	7
	Medium	6	7	8
	High	7	8	9

Figure 36: Insider Threat Level Examples, from Kandias et al. (2010)

While the model provided by Kandias *et al.* (2010) helps in quantifying characteristics of insider threats, there is little help with understanding probabilities of attacks that would be beneficial in simulated environments. To address this, there are several applicable models which use, for example, bayesian networks or agent-based modeling.

Axelrad *et al.* (2013) demonstrated that a bayesian network can be used with survey input of critical variables identified for modeling insider threat behaviour[246]. Their hypothsis revolved around the idea that *degree of interest* is the determining factor for an individual commiting insider therat behvaviour. An ordered list (by weight of importance) of 83 variables were considered in the network to produce a score for an individual's interest in insider threat behaviour. Variables were included on three criteria: (1) whether they are measurable, (2) they have an association value of at least 0.15 with *degree of interest*, and (3) are unique among other variables. Distinct categories of variables were identified:

1) Dynamic environmental stressors
    - Overall environmental stress; Personal and job stressors; Hostility
2) Static personal characteristics
    - Agreeableness; Concientiousness; Extraversion; Openness to experience
3) Dynamic personal characteristics
    - Affect; Attitude
4) Insider actions, or counterproductive behaviour (CPB)
    - CPB-I: Interpersonal conflict or social isolation
    - CPB-O: Rule-breaking
5) Degree of interest
    - Related to: excitement seeking; neurotocism; environmental stressors; hostility; capability
    - Inversely related to: job satisfaction; agreeableness; concientiousness

These are presented in a conceptual model, as follows, where associations are subsets of variables within each category:

[246] E. T. Axelrad, P. J. Sticha, O. Brdiczka and J. Shen, "A Bayesian Network Model for Predicting Insider Threats", *2013 IEEE Security and Privacy Workshops*, IEEE, 2013, pp. 82-89.

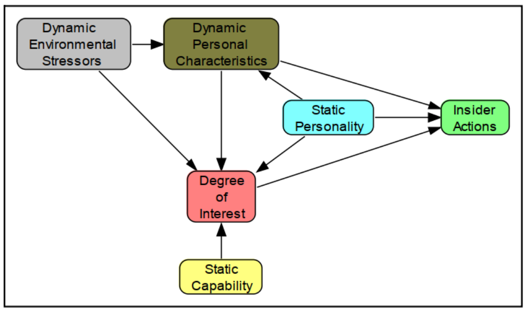

Figure 37: Variable Categories for the Bayesian Network, from Axelrat et al. (2013)[247]

To validate the model, data collection was conducted via voluntary questionnaire for a hypothesized structural equation model (SEM), which provided feedback to improve the Bayesian network. The authors found that the model performed reasonably well, with the final Bayesian network displayed below. For adoption into CyberFactory#1, the relationships and weights between variables will need to be adjusted based on empirical evidence, but the overall structure of the Bayesian network has been validated.

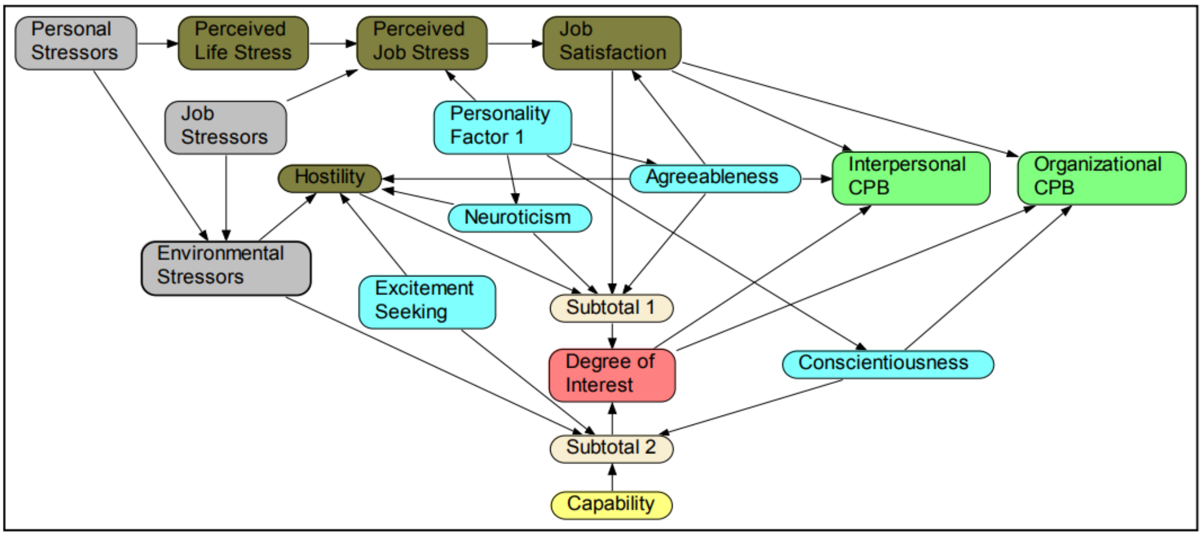

Figure 38: Bayesian Network for Predicting Insider Threats, from Axelrat et al. (2013)[248]

The final model to be discussed is from Sokolowski, Banks and Dover (2016), who use an agent-based modelling approach to predicting insider threats[249]. They argue that disposition, motive and opportunity are the significant elements when predicting an insider threat. Disposition is changed on an agent-by-agent basis from changes in emotional, rational and social factors. Change is influenced from organisational culture and risk/reward perceptions. After a particular threshold is passed, an agent makes a transition to become an active threat (in this way, disposition is a binary condition)[250].

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[247] Ibid.
[248] Ibid.
[249] Sokolowski, C. M. Banks and T. J. Dover, "An Agent-based Approach to Modeling Insider Threat", *Computational and Mathematical Organization Theory*, Vol. 22 No. 3, 2016, pp. 273-287.
[250] Ibid.

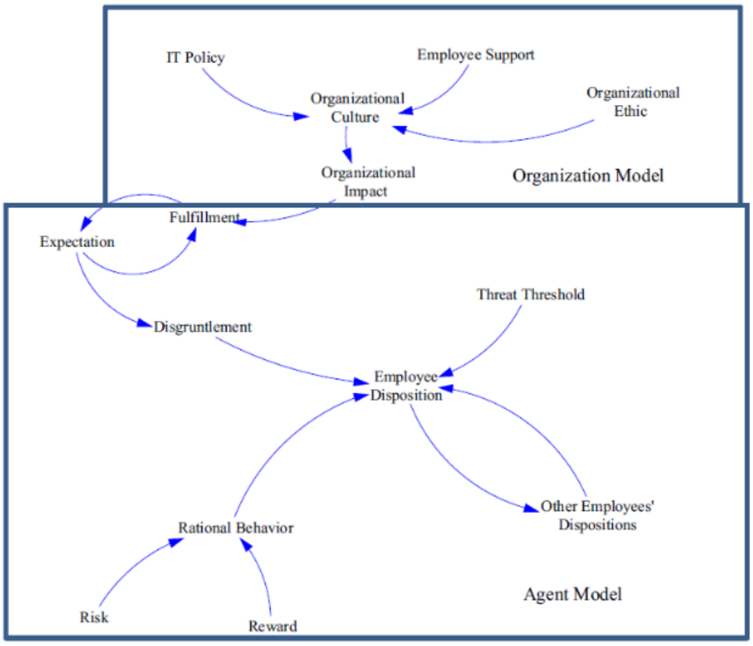

Figure 39: An Agent-Based Insider Threat Model, from Sokolowski et al. (2016)

At the heart of their model, an agent's fulfilment is compared with their expectations to determine whether they are disgruntled. At any point in time, an agent's expectations can be evaluated according to the following equation, with ***p*** primacy weight and ***r*** recency weight and ***c*** consistency weight[251]:

$$E_{j+i} = \frac{(F_1 p + \left(\frac{\sum_{i=1}^{j} F_i}{j}\right) c + F_1 r)}{(p + c + r)}$$

Disgruntlement is computed from expectation (E) and fulfullment (F) at a point in time (j) with an agent-specific affective factor (***a***) as follows[252]:

$$d_i = (E_j - F_j) * a$$

A given agent's social component is the summation of all other agents' dispositions with weights indicating influence between agents. An agents disposition is then given by the following equation, with ***P_i(t)*** representing the risk/reward payoff probability[253]:

$$D_i^{tot} = d_i(t) + P_i(t) + \sum_{j \neq i} \omega_{ij} D_j^{solo}(t)$$

Emotion is captured by evaluating an agent's ability to derive fulfilment from the organisational environment, which is characterized with the factors ***culture*** and ***impact***. Culture contains parameters support, policy and ethics, measuring how an agent perceives its organisation, each on a scale from zero to one. A score of zero lowers expectations while a score of one raises expectations. Support refers to how well an agent is supported in their duties, policy relates to the intrusiveness of policy against the use of systems and ethics is the perception of the organisations behaviour from the agents.

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251 Ibid.
252 Ibid.
253 Ibid.

The authors show their model is capable of producing reasonable results. Such an agent-based approach would be applicable for CyberFactory#1, but will require attention on developing appropriate measures for fulfilment, risk/reward perception and threat thresholds.

4.4. Human Cognitive Behavior

Human to human and human to machine interactions are subject to humans physical and cognitive capabilities. Cognition refers to mental processes, like attention, memory and understanding. Attention is the cognitive process of paying attention to one aspect of the surroundings but disregarding others. In an increased digitalized shop floor, workers interact with intelligent systems, including robots, in a closer and cooperative way. The perception and modeling of human actions, and behaviors, like their attention, awareness, fatigue, is thus crucial.

In this section we will explore emotion recognition techniques, with a focus on non-intrusive and open source ones. The goal is to explore how emotion interacts and influences other domains of cognition, in particular fatigue, attention, memory and rezoning. A survey on actual applications will be done to highlight how CyberFactory#1 can go beyond the state of the art in improved human-machine collaboration by exploring these techniques, to be further explored in WP4 with a survey on cognitive manufacturing for optimization in Industry 4.0.

Cognitive manufacturing explores the analysis of the huge amount of data that come from the cyber-physical components in manufacturing, the advent IoT and the usage of biological and neurological inspired techniques to extract and analyze knowledge from the data, to prepare industrial control systems for unforeseen conditions and to prevent them from failures and other unexpected occurrences that can interfere with the regular behavior, and even more, to optimize the industrial systems according with the contextual conditions. This is a market with a CARG estimated at the end of 2019, as 11%.

Affective computing traditional applications are in the health sector. This is a field with an estimated CARG of 32.3%[254]. Considering affective computing techniques in the field of cognitive manufacturing to address the challenges that Industry 4.0 introduce, is a new step that can benefit shop floor from the optimization, safety and security points of view, in what relates with human-machine collaboration, and in particular in human collaboration with robots.

Emotion plays an important role, not only in the way people communicate, but also in the decision process and knowledge acquisition, influences the perception, and the way rational decisions are made[255][256]. The field of affective computing (AC) improves mechanisms that are able to recognize, interpret and simulate human emotions[257] so

[254] https://www.marketsandmarkets.com/Market-Reports/affective-computing-market-130730395.html

[255] J. S. Lerner, Y. Li, P. Valdesolo, and K. S. Kassam, "Emotion and Decision Making," Annu. Rev. Psychol., 2015, doi: 10.1146/annurev-psych-010213-115043.

[256] D. S. Massey, "A brief history of human society: The origin and role of emotion in social life," Am. Sociol. Rev., 2002, doi: 10.2307/3088931.

[257] R. W. Picard et al., "Affective learning - a manifesto," BT Technol. J., vol. 22, no. 4, pp. 253–268, Oct. 2004, doi: 10.1023/B:BTTJ.0000047603.37042.33.

closing the gap between human and computer. The AC concept was introduced by Rosalind Picard in 1995 as a tool to improve human-machine interfaces by containing emotional references.

A key question is "how to recognize emotions?" the AC techniques aim is to get this information from the human body. First, it should be able to recognize the physical aspects of the human body, such as facial expression, speech intonation and body movements and gestures.

In this section, we intend to bring an overview about how emotions can be detected and considered as modeling human behavior.

4.4.1. Emotion, Cognition and Behavior

Human to human communication is influenced by a mix of audio-visual and sensorial signals. Emotion plays an important role, not only in the way people communicate, but also in the decision process and knowledge acquisition. It influences the perception, and the way rational decisions are made thus, it is important to understand the effect of emotion in human behavior. One of the problems of studying emotions is defining them, as well as defining the terms associated to it. Nearly hundreds of definitions of emotion have been registered[258]. To analyze emotion there are several theories, which attempted to specify the interrelationships of all the components involving an emotion and the causes, the reasons and the function of an emotional response. Even though there are several works describing these approaches, some of these theories are very controversial among the intellectual community.

Emotions have two components: the mental component (cognitive) and the physical component (body) which can be classified in three categories: primary, secondary and tertiary emotions. Primary emotions take place as a response to some kind of event, which can cause a visible physical response and trigger emotions such fear, joy, love, sadness, surprise, anger. These emotions can cause other sub-categories as shown in Table 5.

[258] Dixon, T. (2012). Emotion: The history of a keyword in crisis. In *Emotion Review* (Vol. 4, Issue 4, pp. 338–344). SAGE Publications. https://doi.org/10.1177/1754073912445814.

Table 5 - Emotions

Primary Emotions	Secondary Emotions	Tertiary Emotions
Fear	Nervousness	Anxiety, Apprehension, Distress, Dread, Tenseness, Uneasiness, Worry
	Horror	Alarm, Fright, Hysteria, Mortification, Panic, Shock, Terror
Joy	Cheerfulness	Amusement, ecstasy, gaiety, euphoria, bliss, elation, delight, happiness, jubilation
	Zest	Enthusiasm, excitement, exhilaration, thrill, contentment, relief, optimism, pride, enthrallment
Love	Affection	Fondness, attraction, adoration, sentimentality, caring
	Lust	Arousal, desire, passion, infatuation, obsession
	Longing	Longing
Sadness	Suffering	Agony, hurt, anguish
	Disappointment	Dismay and displeasure
	Shame	Guilt, remorse and regret
	Neglect	Insecurity, alienation, homesickness, embarrassment, humiliation
	Sadness	Depression, unhappiness, misery, melancholy, gloom, despair
	Sympathy	Pity, sympathy
Surprise	Surprise	Astonishment, amazement
Anger	Rage	Fury, wrath, bitterness, loathing, resentment, hate, loathing, Frustration and exasperation
	Irritation	Agitation, aggravation, grouchiness
	disgust	Revulsion, contempt, jealousy and torment
	Exasperation	Exasperation, frustration
	Envy	Envy, jealousy
	Torment	Torment

Cognition refers to the mental processes, like attention, memory and understanding. Attention is the cognitive process of paying attention to one aspect of the surroundings but disregarding others. Emotions also play an essential role in the process of paying attention.

If a person feels anxious, sad or depressed, it is very hard to concentrate and to pay attention. Moreover, it is very hard to pay attention if individuals are tired, sick or not feeling well[259]. The study of mental fatigue has never been more imperative than in the times in which we live. Since mental fatigue causes cognitive impairment and this has been one of the most important reasons of accidents and is considered one of the major causes for human error[260].

4.4.1.1. Emotions recognition

The field of affective computing (AC) improves mechanisms that are able to recognize, interpret and simulate human emotions, so closing the gap between human and computer. The AC concept was introduced by Rosalind Picard in 1995 as a tool to improve human-machine interfaces by containing emotional references.

A key question is "how to recognize emotions?" the AC techniques aim is to get this information from the human body. First, it should be able to recognize the physical aspects of the human body, such as facial expression, speech intonation and body movements and gestures.

4.4.1.2. Facial Expressions Recognition

A facial expression is the result of the actions or positions of face muscles. Facial expression recognition (FER) plays an important role in the communication of human and machines as it tries to near de gap between the two. Most of FER research was based on the work of Ekman. His work was based on the supposition that the emotions are universal across individuals as well as human ethnics and cultures.

The work conducted by Ekman and Friesen developed the Facial Action Coding System (FACS), which is a manual method for measuring the facial expressions. FACS can code any physically possible facial expression, breaking it down to a specific Action Units (AU) that classifies independent face motion in a temporal order. Manually coding a segment of video is a timely method performed by highly trained human experts. Each minute of video takes nearly an hour to code. Research on this subject tries to automate this technique.

Nowadays, advancements on computer vision and Artificial Intelligence (AI) fields make it possible to increase the precision and speed of facial emotion classification like anger, disgust, fear, happiness, sadness and surprise recognition.

The evolution of facial expression recognition, techniques of face tracking and feature extraction methods was significant across time, developing a wide range of models such as: Active Appearance Models, Optical flow models, Active Shape Models, 3D Morphable Models, Muscle-based models, 3D wireframe models, Elastic net model, Geometry-based

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[259] Pimenta, A., Carneiro, D., Neves, J., & Novais, P. (2016). A neural network to classify fatigue from human-computer interaction. *Neurocomputing*, *172*, 413–426. https://doi.org/10.1016/j.neucom.2015.03.105.

[260] Tanaka, M. (2015). Effects of Mental Fatigue on Brain Activity and Cognitive Performance: A Magnetoencephalography Study. *Anatomy & Physiology*, *s4*. https://doi.org/10.4172/2161-0940.s4-002.

shape models, 3D Constrained Local Model, Generalized Adaptive View-based Appearance Model[261].

4.4.1.3. Body Language

Body language is way of non-verbal communication giving important hints about the emotions, and motivations of an individual[262]. It has been advocated that body language plays a large role in day-to-day communication. There are several forms of body language that can be used to recognize emotion or intent.

Gestures can be some of the most recognizable signals of body language. Waving, pointing, and using the fingers to indicate numbers are all very simple gestures to understand. In the other hand, some gestures may be cultural[263], like a thumb-up or a peace sign. Nevertheless, these gestures could have different meaning in different cultures.

Arms and legs can also indicate nonverbal information and in some studies this information can be linked to emotions. In addition, the posture can give hints to the state of mind. In general, most methods of detection of body show naive geometrical representation, either skeletal or based on independently identification of parts of the body.

4.4.1.4. Eye Tracking

As we do day-to-day tasks, like participate in a conversation, our eyes movements are a natural and essential part of this process. These movements include whether individuals are making direct eye contact or avoiding it if they are blinking, or if their pupils are dilated.

Eye tracking is a technique that allows the measuring of the position and behavior of eye movement. The analysis of the eyes and their characteristics can be used to measure the human response to visual, auditory or sensory stimuli. It is a common technique in research of the visual system, psychology, linguistics and, in recent years, its range of application has extended to consumer behavior, enabling marketers to understand what information and visual aspects consumers directly are gazing to. Not only is eye tracking used to detect mental fatigue and drowsiness mostly in the automobile industry, but other studies also combine the eye tracking with the use of the mouse and keyboard on computer[264].

4.4.1.5. Emotional Speech Recognition

Speech recognition consists in the capability of a program in recognizing words or phrases from the verbal language. The main application of speech recognition resides in aided

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[261] Poria, S., Cambria, E., Bajpai, R., & Hussain, A. (2017). A review of affective computing: From unimodal analysis to multimodal fusion. *Information Fusion*. https://doi.org/10.1016/j.inffus.2017.02.003.
[262] Tipper, C. M., Signorini, G., & Grafton, S. T. (2015). Body language in the brain: Constructing meaning from expressive movement. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2015.00450.
[263] https://www.verywellmind.com/what-is-cross-cultural-psychology-2794903
[264] Pimenta, A., Carneiro, D., Neves, J., & Novais, P. (2016). A neural network to classify fatigue from human-computer interaction. *Neurocomputing*, *172*, 413–426. https://doi.org/10.1016/j.neucom.2015.03.105.

technology to assist people with disabilities. The purpose of Speech Emotion Recognition (SER) is to identify the individual emotional state in his/her speech signal. There are several issues that fundamental in constructing a good SER system, first a good emotional speech database, second extracting effective features, and last designing reliable classifiers using machine learning algorithms.

The advances in SER, brought many classification algorithms, like the Gaussian mixture model (GMM), hidden Markov model (HMM), support vector machine (SVM) neural networks (NN), and recurrent neural networks (RNN)[265].

There are several applications of recognize emotion of the individual like in the interface with robots, audio surveillance, web-based E-learning, commercial applications, clinical studies, banking, call centers, computer games[266].

4.4.1.6. Multimodality of Emotion Recognition

Several points of view state that an emotion response has multiple manifestations both physical and behavioral. Also, the human computer paradigm advocates that in the future human centered interfaces should have the capacity to sense changes in user affective behavior. So, the development of affective Multimodal Human-Computer Interaction (MHCI) is growing.

MHCI depend on different areas of study such as computer vision, artificial intelligence, psychology and others. The study of MHCI involves the understanding of three variables: user, system and the interaction between them. To understand the dynamic between these variables is possible to construct new systems more friendly and intuitive thus, more practical. Therefore in a near future is likely to include new ways of interaction between humans and computers, such as: visual interaction (facial expression, head pose, gesture, body movement and postures), auditory (pitch, loudness, speaking rate), tactile (heart rate, skin conductivity), brain signals (EEG) and many others.

4.4.1.7. Emotion recognition tools

Today, with the developments on AI, there's an increase number of applications and API-accessible software online that have the ability to discern emotive gestures. These applications use facial detection, eye tracking, body language, and speech analyses, among others to interpret moods from photos, videos, and speech. Today, over 20 emotions can be recognized with these applications and APIs.

This section describes the open source tools that are used for emotion recognition. This includes the ability of AI tools to recognize emotions from: faces, voices, behavior and even from a mix of sources.

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[265] Lim, W., Jang, D., & Lee, T. (2017, January 17). Speech emotion recognition using convolutional and Recurrent Neural Networks. *2016 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference, APSIPA 2016*. https://doi.org/10.1109/APSIPA.2016.7820699.

[266] Kerkeni, L., Serrestou, Y., Mbarki, M., Raoof, K., Ali Mahjoub, M., & Cleder, C. (2020). Automatic Speech Emotion Recognition Using Machine Learning. In *Social Media and Machine Learning*. IntechOpen. https://doi.org/10.5772/intechopen.84856.

4.4.1.8. Facial emotion recognition

With facial emotion recognition, the algorithms recognize faces from an image or video, and interpret the micro expressions by analyzing the connection between points on the face, based on databases compiled in academic environments[267].

- **OpenFace**

OpenFace 2.0[268] is a framework that implements modern facial behavior analysis algorithms containing: facial landmark detection, head pose tracking, eye gaze and facial action unit recognition. The analyses of all these human behaviors together or individually, play an important role in understanding emotion and human conduct. For instance, facial landmarks permit the understanding of facial expression movement and its purpose, allows for face alignment for various tasks such as age appraisal and gender detection. Head pose helps to determine emotion and social signal perception and expression. Gaze direction is significant when appraising things like attention and social skills, also the strength of emotions. Facial expressions disclose intent, display affection and emotion[269].

OpenFace 2.0 for facial behavior analysis uses different technologies. For facial landmarks detection and tracking, OpenFace 2.0 uses the Convolutional Experts Constrained Local Model (CE-CLM)[270]. This mode uses the Point Distribution Model (PDM) that captures landmark shape variations and patch experts that model local form variations of each landmark. In addition, to facial landmark detection OpenFace 2.0 is capable to estimate the head pose, as CE-CLM internally uses a 3D representation of facial landmarks and projects them to the image using orthographic camera projection. To estimate eye gaze, OpenFace 2.0 uses Constrained Local Neural Field (CLNF) to discover eyelids, iris, and the pupil. They used for training the landmark detector the SynthesEyes training dataset[271]. Facial expressions are recognizing through the presence of facial action unit (AU). OpenFace 2.0 uses a framework based on linear kernel Support Vector Machines.

OpenFace 2.0 was design to for people interested in implementing interactive applications and can to run from a simple webcam without any specialist hardware. OpenFace 2.0 can be used as: Graphical User Interface (for Windows), or command line (for Windows, Ubuntu, and Mac OS X). The existing open source code can be integrated in any C++, C, or Matlab project. OpenFace 2.0 can operate on real-time data video feeds from a webcam, recorded video files, image sequences and individual images.

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[267] Ko, B. C. (2018). A brief review of facial emotion recognition based on visual information. *Sensors (Switzerland)*, *18*(2). https://doi.org/10.3390/s18020401.
268 https://github.com/TadasBaltrusaitis/OpenFace
[269] Baltrusaitis, T., Zadeh, A., Lim, Y. C., & Morency, L. P. (2018). OpenFace 2.0: Facial behavior analysis toolkit. Proceedings - 13th IEEE International Conference on Automatic Face and Gesture Recognition, FG 2018, 59–66. https://doi.org/10.1109/FG.2018.00019.
[270] Zadeh, A., Baltrušaitis, T., & Morency, L.-P. (2016). Convolutional Experts Constrained Local Model for Facial Landmark Detection. http://arxiv.org/abs/1611.08657.
[271] Wood, E., Baltrušaitis, T., Zhang, X., Sugano, Y., Robinson, P., & Bulling, A. (n.d.). Rendering of Eyes for Eye-Shape Registration and Gaze Estimation. Retrieved May 19, 2020, from http://www.3dscanstore.com/.

- **EmoPy**

EmoPy[272] is an open source a FER toolkit that aims to search the field of FER using existing public datasets, and make neural network models which are free, and easy to integrate into different projects. EmoPy is developed as part of ThoughtWorks Arts, a program which incubates artists investigating intersections of technology and society. The behavior of EmoPy system is highly dependent on the available data, and the developers of EmoPy created and tested the system using only publicly-available datasets. Originally, several models were trained and built-in as part of EmoPy. According to EmoPy's creators, the best performing architecture was a Convolutional Neural Network. The present models were trained on the Microsoft's FER2013 and the Extended Cohn-Kanade datasets. EmoPy runs using Python 3.6 and up and runs on any Python-compatible OS.

- **Face classification and detection.**

Real-time face classification and detection[273] that permits the detection of emotion and gender classification using datasets with convolutional neural network (CNN) model and OpenCV. The dataset used were the IMDB for gender classification, containing a large array of photos with gender and age labels. Also, the dataset fer2013 was used for emotion classification where the images are categorized based on the emotion shown in the facial expressions. The study reports accuracies of 96% in the gender dataset and 66% in the emotion dataset, classifying in the following seven classes: angry, disgust, fear, happy, sad, surprise and neutral.

This system has been validated by its deployment on a Care-O-bot 3 robot[274]. The Care-O-bot 3 robot is the product vision of a mobile robot assistant that can assist humans in domestic environments like fetch and carry tasks, entertainment, assisted cleaning in office buildings or in emergencies. The robot using the face classification and detection algorithms is able to extract information from the face of its user and recognize the emotional state or detect the gender.

All the information about this study is made available in a public repository[275].

[272] https://github.com/thoughtworksarts/EmoPy
[273] Arriaga, O., Valdenegro-Toro, M., & Plöger, P. (2017). Real-time Convolutional Neural Networks for Emotion and Gender Classification. ESANN 2019 - Proceedings, 27th European Symposium on Artificial Neural Networks, Computational Intelligence and Machine Learning, 221–226. http://arxiv.org/abs/1710.07557.
[274] Reiser, U., Jacobs, T., Arbeiter, G., Parlitz, C., & Dautenhahn, K. (2013). Care-O-bot® 3 – Vision of a Robot Butler (pp. 97–116). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-37346-6_9.
[275] https://github.com/oarriaga/face_classification

Table 6 – Facial emotion recognition tools

Application	Programing Language	year	Video/image	Eye tracking	Emotion	Detected points
Open face	C++	2019	Video	yes	Action units	Detects several points on the face
EmoPy	Python	2020	Image	No	Angry, disgust, fear, sad, happy, sad, surprised neutral	-
Face classification	Python	2019	Video	No	Angry, disgust, fear, sad, happy, sad, surprised neutral	Rectangular face / no face points

- **Fatigue Detection**

Fatigue detection technology for industry workers is extremely important. The cost of fatigue is of growing concern to organizations as fatigue-related accidents and losses are extremely high. Fatigue can be defined as the feeling of tiredness, exhaustion or lack of energy to accomplish tasks in an effective manner. This can be classified as physical or mental fatigue. When a worker is fatigue or deprived of sleep, there is natural tendency for the eyes to close. For fatigue detection car industry take the lead develop safety technology, which aims to prevent accidents when the driver is getting drowsy. A computer vision system made with the help of OpenCV that can automatically detect driver drowsiness in a real-time video stream and then play an alarm if the driver appears to be drowsy.

The algorithm[276] to detect eye blinks by using a recent facial landmark detector. A single scalar quantity that reflects a level of the eye opening is derived from the landmarks. Having a per-frame sequence of the eye opening estimates, the eye blinks are found by an SVM classifier that is trained on examples of blinking and non-blinking patterns.

[276] Cech, J., & Soukupova, T. (2016). Real-Time Eye Blink Detection using Facial Landmarks. In Center for Machine Perception, Department of Cybernetics Faculty of Electrical Engineering, Czech Technical University in Prague. https://doi.org/10.1017/CBO9781107415324.004.

Table 7 - Fatigue

Application	Programing Language	year	Video/image	Eye tracking	Detected points
Fatigue (Drowsiness) Detection using OpenCV	Python	2019	Video	yes	Eye points

4.4.1.9. Speech emotion recognition

- **Deep Speech**

The Deep Speech[277] is a system that uses deep learning combined with a language model. This approach leads to a higher performance record than traditional methods[278]. It uses two sets of scenarios: clear, conversational speech and speech in noisy environments. This approach is enabled by multi-GPU training and by data collection and synthesis strategies to construct a large training sets exhibiting the distortions.

- **Speech Emotion Recognition**

The Speech Emotion Recognition[279] uses machine learning to recognize emotions present in a speech sample. For this system seven emotions where considered: neutral, anger, disgust, fear, happy, sad, surprise.

The speech sample is processed through the pipeline: 1) Raw waveform; 2) Spectrogram; 3) Log-Mel Spectrogram; 4) Convolutional Neural Network (CNN); 5) Output (one or more of the seven emotions)

- **Speech-Emotion-Analyzer**

The Speech Emotion Analyzer [280] is a machine-learning model that is capable of detecting five different male/female emotions from audio speeches. This project has multiple applications from the industries that offer different services like marketing company suggesting you to buy products based on your emotions, automotive industry can detect the individual emotions and adjust the speed of autonomous cars as required to avoid accidents.

Table 8 – Speech emotion recognition tools

Application	Programing Language	Year	Type
Deep Speech	Python	2020	Speech to text
Speech Emotion Recognition	Python	2020	Emotion in speech

[277] https://github.com/mozilla/DeepSpeech
[278] Hannun, A., Case, C., Casper, J., Catanzaro, B., Diamos, G., Elsen, E., Prenger, R., Satheesh, S., Sengupta, S., Coates, A., & Ng, A. Y. (2014). Deep Speech: Scaling up end-to-end speech recognition. http://arxiv.org/abs/1412.5567
[279] https://github.com/Brian-Pho/RVST598_Speech-Emotion-Recognition
[280] https://github.com/MITESHPUTHRANNEU/Speech-Emotion-Analyzer

Speech-Emotion-Analyzer	Python	2018	Emotion in speech

4.4.1.10. Behavior recognition

- **OpenPose**

OpenPose[281] is a real time multi person key point detection library for body, face, hands, and foot appraisal, detecting in total 135 key points on an image. This project is a real time multi-person 2D pose appraisal, enabling machines to visually recognize and understand humans and their relations. The key points detected indicate both position and orientation of human limbs. The program shows a mixture body and foot appraisal into a single model boosts the accuracy of each component individually running them sequentially. The algorithm parses of body poses, and preserves efficiency despite of the number of people involved. The library is been used for several research topics involving human analysis, such as human identification and Human-Computer Interaction. OpenPose was included in the OpenCV library[282].

Table 9 – Speech emotion recognition tools

Aplication	Programing Language	Year	Video/image	Detected points
OpenPose	Python	2020	Video or image	body, face, hands, and foot

4.4.1.11. Multimodal emotion recognition

If we combine several different types of emotion recognition, we have a multimodal system. It is interesting to merge the multimodal emotional information retrieved by numeral technics analysis.

The multimodal emotion recognition[283] project combines three forms of emotion recognition facial, speech and textual emotions, for an interview simulator, using a deep learning based approaches.

The project is contains three pipelines one for each form of emotion recognition:

- The facial emotional recognition pipeline has the following configuration: 1) Launch the webcam; 2) identify the face by Histogram of Oriented Gradients; 3) Zoom on the face; 4) Dimension the face; 5) Make a prediction on the face using our pre-trained model. The prediction includes the number of blinks on the facial landmarks on each image.
- The speech emotional recognition pipeline has the following configuration: 1) Voice recording; 2) Audio signal discretization; 3) Log-mel-spectrogram extraction; 4) Split

[281] https://github.com/CMU-Perceptual-Computing-Lab/openpose
[282] Cao, Z., Hidalgo, G., Simon, T., Wei, S.-E., & Sheikh, Y. (2018). OpenPose: Realtime Multi-Person 2D Pose Estimation using Part Affinity Fields. ArXiv, 2017-Janua(Xxx), 1302–1310. http://arxiv.org/abs/1812.08008
[283] https://github.com/maelfabien/Multimodal-Emotion-Recognition

spectrogram using a rolling window; 5) Make a prediction using our pre-trained model.

- The text emotional recognition pipeline has the following configuration: 1) Text data retrieving; 2) Custom natural language pre-processing; 3) Prediction using our pre-trained model.

Table 10 - Multimodal emotion recognition

Aplication	Programing Language	Year	Combination of technics
Multimodal Emotion Recognition	Python	2019	Facial, speech and textual

4.4.1.12. Related Projects

In this section we enumerate some research projects that we consider to approach as they also address the human cognitive behavior, including considerations about the emotional and/or affective side of it.

EmoSpaces[284]: EmoSpaces stands for Enhanced Affective Wellbeing based on Emotion Technologies for adapting IoT spaces. The project goal is the development of an IoT platform that determines context awareness with a focus on sentiment and emotion recognition and ambient adaptation. Two different environments have been considered: a living room and a kitchen. The system uses a deeply optimized Hough transform algorithm and a voting scheme to classify the different activities. There's an application with the aim to detect and analyze human daily behavior. Clustering techniques are used to detect unusual behaviors or events, and to track successive activities made by the person occupying the smart home. Hapicare is a patient services portal offering an application for monitoring vital parameters collected by practitioners, connected objects and smart AI engines. This application tracks changes in the sleeping patterns, meal daily dietary patterns, Self-measurement of vital signs, exercise frequency and detects prolonged negative emotions.

Emphatic[285]: The mission of the Emphatic project is to provide state of art solutions and applications on affective technologies, such as facial expression analyzers, gesture recognition and interpretation, human body pose estimation, physiological affective wearables, Speech recognition, emotion interpretation from audio cues, Textual analyzers, Emotion analysis from interaction devices.

Humane-AI[286]: Humane-AI project goal is to develop intelligent systems that interact and collaborate with humans, and enhance human abilities and empower both individuals and

284 https://itea3.org/project/emospaces.html
285 https://itea3.org/project/empathic.html
286 https://www.humane-ai.eu/

society. The Humane-AI project aims to empower the multi-model perception of AI systems, in another words, AI system perception and interaction in complex real-world environments; AI capability to provide self-explanations, understand the learning, reasoning and planning processes of AI systems; Comprehensive modeling; Human and AI interaction, develop paradigms that allow humans and AI agents to interact and collaborate; Understand the impact of complex networks in large-scale communities over various temporal and spatial scales; AI Ethics, Law and Responsibility, this is, the AI design should be aligned with ethical principles and human values.

Cosibas[287]: This project aims to integrate semantic and cognitive AI technologies into IoT-based applications. The integration of AI services on both architectural and logical levels are going to be made in two case studies: Smart Grid and Sea Traffic management. The project contributions are the development of cognitive layers that will support scalability and a large-scale of heterogeneous IoT-based systems; Deliver intelligent business applications and systems like decision making management, efficient data analysis and inference, and cognitive assistants with adaptive user-specific interfaces. Create a fault forecasting module, to predict maintenance and schedules of IoT devices, create elastic architectures capable of adapting to context changes but able to keep the service quality over the entire system's life-cycle. Create IoT decision support services and assistants that are able to evaluate the current semantic context and suggest possible decisions.

Papud[288]: stands for Profiling and Analysis Platform Using Deep Learning. The goal of the project is to aggregate various Machine Learning and Data Mining technologies, such as Theano and TensorFlow, to produce novel text analytics algorithms. PAPUD will receive data from sources including emails, surveys, machine logs, voice to text data, videos allowing to create Deep Learning models through technological collaboration. This will enable PAPUD to understand the data's semantics and perform complex operations, such as summarization, sentiment analysis and weak signals detection. Five use cases have been identified in order to demonstrate the project aims within different domains: e-commerce; call center; recommendation system for human resources; behavior analysis for reverse efficient modelling and prescriptive maintenance for HPC. Regarding the Behavior Analysis for Reverse Efficient Modelling case study, the project focus on analyzing log files with user activity on web sites, to reconstruct navigation sessions and extract recurring patterns; and to sentiment analysis with a focus on quantifying the frustration level resented by the users using non-intrusive and privacy preserving sensors.

[287] https://itea3.org/project/cosibas.html
[288] https://itea3.org/project/papud.html

4.5. Summary: Humans in the Factory of the Future

With the transition of factories to industry 4.0, human behavior can be expected to change as well. There is currently still a lack of understanding of these processes and a lack of data on behavioral attitudes and their impact on the ecosystem of the FoF.

In the field of experimental economy, the limitation is not within the availability of models, but rather the lack of data. There is still too little research into the profiles of shop-floor workers, or the relationship between these profiles and the work done by these workers (and how this is influenced by the transition towards more advanced factory floors). Following a socio-psychological and experimental economics approach, the data and analysis of CF#1 will provide an overview of who the human workers in the FoF are, how they behave and what their attitudes are. In combination with an analysis of subjective job satisfaction indicators and the development of a multi-dimension index of job quality, it will possible to define both who the "average worker" in the factory of the future is and how (s)he differs from the average worker in the factory of today. This profile of the average worker could, in principle, be included in simulations of the FoF and its operation. More generally, this research will produce a rich dataset at two points in time, which can be made available and adapted for further simulations.

For humans in cybersecurity there is a need to consider personal factors that influence reliability, such as stress, attitudes and job satisfaction. An understanding of these factors and how they influence reliability was explored with a review of common modelling techniques. While errors due to reliability failures are unintentional, there is another source of potential risk caused by workers in the factory: insider threats. The characteristics of insider threats should be understood at the forefront of industry 4.0 to ensure that vulnerability mitigation capabilities are in place as new technologies are introduced.

Essentially, the work in this filed aims to enable detection (and possibly classifying) of misconduct and insider threats. As a traditional factory shifts towards the FoF, stressors, motivators, etc., will change and there is an expectation of an increased (or decreased) occurrences of such events. This work will firstly focus on the "monitoring and classifying" part of cybersecurity with regard to human elements. Further work could include co-simulation of a human operator and some factory system, which would help to demonstrate available cybersecurity capabilities in Task 3.3.

Human emotions and the detection of thereof plays a vital role within the human to human as well as human to machine interactions. Due to an increased digitalized shop floor, workers interact with intelligent systems, including robots, in a closer and cooperative way. The perception and modeling of human actions, and behaviors, like their attention, awareness, fatigue, is thus crucial.

In the section on human cognitive behavior several emotion recognition techniques were explored, with a focus on non-intrusive and open source ones. A survey on actual applications has been done to highlight how CyberFactory#1 can go beyond the state of the art in improved human-machine collaboration by exploring these techniques, which will be further explored in WP4 with a survey on cognitive manufacturing for optimization in Industry 4.0.

5. Factory SoS Modelling

5.1. Introduction & General Approach to Factory SoS Simulation

In the next 10 to 15 years, factories and plants across industry sectors will be high-tech engines of mass customization, able to respond quickly and effectively to changing customer and market demands. Highly automated and information-intensive, the factory of tomorrow will look like an integrated hardware and software system. This system will be fuelled by vast quantities of information from every corner of the enterprise and beyond, moderated by analytical systems that can identify and extract insights and opportunities from that information, and comprised of intelligent machines that learn, act, and work alongside highly skilled human beings in safe and collaborative environments.

Specifically, the key trends are[289]:

- **Digitization** is transforming how manufacturers need to think about human capital management. The workforce will need greater digital literacy and to have high-tech and collaboration skills. It will also need to be able to work cross functionally as well as with increasingly intelligent machines to bring higher levels of efficiency and productivity to the enterprise;
- Future factory designs and footprints will likely favour modularization, with micro factories capable of **mass customization** using such technologies as 3D printing as well as **digital manufacturing technologies**;
- The manufacturing innovation process will evolve to be more open and extended, with **collaborative models** that span internal as well as external constituencies;
- **Supply chains** will become highly integrated, increasingly intelligent, and even self-managing;
- **New business models** incorporating outcome-based services will emerge, enabling manufacturers to diversify their revenue streams and provide greater value to customers;
- Cognitive computing and **analytic techniques** will enable production environments to self-configure, self- adjust, and self-optimize, leading to greater agility, flexibility, and cost effectiveness.

The European Commission started early with the support of the factories of the future by establishing already in 2008, the “Factories of the Future” PPP understanding the necessity to support one of the main European Areas in its transition into the digital world[290].

These so-called "smart factories" demanded by the markets have products and services with shorter and shorter lifecycles and an ever-increasing level of customization. Therefore, responsiveness, flexibility, reconfigurability and modularity become key concepts.

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[289] https://www.intel.com/content/www/us/en/industrial-automation/factory-of-the-future-vision-2030-white-paper.html
[290] http://ec.europa.eu/research/industrial_technologies/factories-of-the-future_en.html

With current (and increasing) levels of complexity, we can speak of Cyber-physical Systems of Systems: as defined in the state-of-the-art literature[291] “A SoS is a system which results from the coupling of a number of constituent systems at some point in their life cycles”. The complexity of CPSoS lies in the interoperability of subsystems that are not necessarily designed to cooperate and work together. Therefore, it is necessary to work to minimize risks of unforeseen and highly undesirable behaviour.

As indicated in some of the most relevant results of the European CPSoS project[292], “the control and management tasks in such systems cannot be performed in centralized or hierarchical top-down manner with one authority tightly controlling to subsystems. In CPSoS, there is a significant distribution of authority with partial local autonomy”. Renier asserts the importance of introducing cognitive features into modern systems in such a way that they support human activity in interaction with complex systems: in particular, the use of algorithms to manage large amounts of data in order to monitor system performance, the Optimal pattern recognition in System Management to be used for adaptability[293]. Namely, the goal is to enable a high-level understanding of the system without going into each individual subsystem’s details, delegating data management and learning processes as much as possible to computational power.

5.1.1. Concurrent Engineering (CE)

Concurrent Engineering (CE) is an engineering method that involves simultaneously engaging all the actors of a project, from the start, in understanding the desired objectives and all the activities that will have to be carried out[294]. Different departments work on the diverse phases of engineering product development simultaneously, emphasising on the parallelisation of tasks using an integrated product team approach[295]. The goal is to improve the productivity of product design and reduce the lead time of product design, as it represents one of the most substantial contemporary approach in the development of new products[296].

Specifically, the European Space Agency (ESA) defines it as following:

> “Concurrent Engineering (CE) is a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life cycle.” [297]

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[291] P. Brook, ““On the Nature of Systems of Systems.”,” in *Presented at INCOSE International Symposium Edinburgh*, Scotland GB, 2016.
[292] http://www.cpsos.eu/wp-content/uploads/2016/04/CPSoS-Brochure-HighRes.pdf
[293] M. A. Reniers, S. Engell and H. Thompson, “Core research and innovation areas in cyber-physical systems of systems.,” *ERCIM News 2015,* pp. 11-13, 2015.
[294] https://afpr.asso.fr/content/assises/2001/info/pr001.htm
[295] "The Principles of Integrated Product Development". NPD Solutions. DRM Associates. 2016. Retrieved 7 May 2017.
[296] Jain, K., and Aggarwal, L. (2009), “Production Planning Control and Industrial Management”Khanna Publishers, Darya Ganj, New Delhi, India
[297] http://www.esa.int/Enabling_Support/Space_Engineering_Technology/CDF/What_is_concurrent_engineering

On the other hand, Winner, et al., define it as:

> "Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including, manufacturing and support. This approach is intended to cause the developers from the very outset to consider all elements of the product life cycle, from conception to disposal, including quality, cost, schedule, and user requirements." [298]

In the past, commercial success was practically guaranteed if manufacturing companies could design, develop, and manufacture high quality products that satisfied the customer's needs at competitive prices. However, starting from the early 1990s this conventional routine drastically shifted as time-to-market became an essential part in commercial success. Indeed, research has shown that being late to market is worse than having a fifty percent cost overrun when these overruns are related to financial performance over the lifecycle of a new product or service. Thus, time has become a major driver of competitive advantage.[299] Concurrent engineering has flourished recently, and is now a clear approach to optimizing design and engineering cycles.[300] CE has been employed in a plethora of enteprises, organizations, and universities, and particularly in the aerospace industry. It was then implemented into the information and content automation field, expanding past the physical product development.

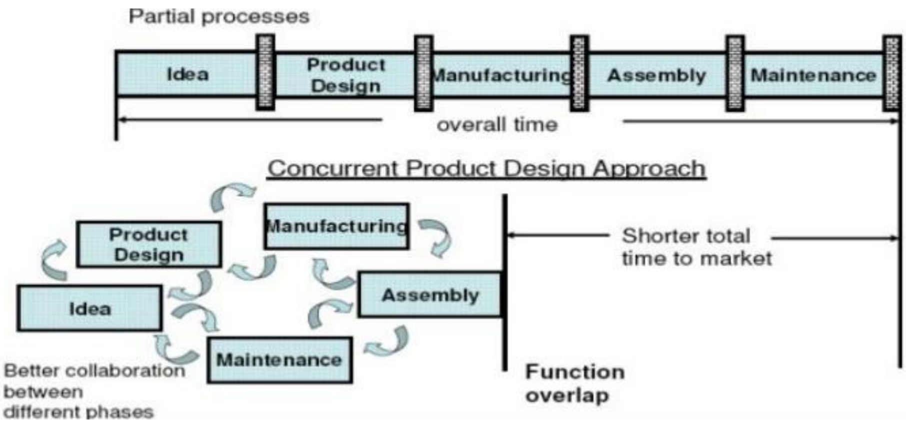

Figure 40: Concurrent product design versus traditional product design

The core philosophy of concurrent engineering is based upon two pillars. First is the notion that all elements of a product's life-cycle—from functionality, production, assembly, testing, maintenance, environmental impact, and finally disposal and recycling—should be meticulously considered in the early design phases.[301] The second is that design activities

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[298] Winner, Robert I., Pennell, James P., Bertrand, Harold E., and Slusarczuk, Marko M. G. (1991). "The Role of Concurrent Engineering in Weapons System Acquisition", Institute for Defense Analyses Report R-338, December 1988, p v.
[299] Debackere, K. (2016), "Concurrent Engineering" [Online] Assessed on 8 October 2016, from http://www.referenceforbusiness.com/management/C omp-De/Concurrent-Engineering.html
[300] Ma, Y., Chen, G. & Thimm, G.; "Paradigm Shift: Unified and Associative Feature-based Concurrent Engineering and Collaborative Engineering", Journal of Intelligent Manufacturing, doi:10.1007/s10845-008-0128-y
[301] Kusiak, Andrew. Concurrent Engineering: Automation, Tools, and Techniques. New York: Wiley, 1993. Print.

should all be occurring simultaneously: its concurrent nature significantly increasing productivity and quality of the product.[302]

Concurrent Engineering aims at improving product development performance. Even though the implementation of CE can lead to impressive results, the adoption rate and to which degree it is adopted vary widely between companies, sectors and countries. As a long-term strategy, it should be considered only by organizations also with long-term strategies. Its implementation involves major organizational and cultural change, requiring the integration of people, business methods, and technology and being dependent on cross-functional working and teamwork rather than conventional hierarchical organization. Here the primary issue is the formation of teams and shared information: collaboration rather than individual effort.[303] According to Sofuoglu, these are the seven elements in team cooperation philosophy : (1) flexible, unplanned and continuous collaboration, (2) commitment to meet the goals, (3) communication (exchange of information), (4) ability to make compromises, (5) consensus in spite of disagreement, (6) coordination (managing interdependencies between activities), and (7) continuous improvements in order to increase productivity and reduce process times.[304]

To successfully implement Concurrent Engineering a strong reliance on practical integration, shared information and collaborative problem solving within the members is needed, as proper communication is key to support the manufacturing strategy. Precise and actualised information on-demand is essential to allow team members to take the right design decisions. [305]

Figure 41: Benefits of CE Implementation. Source: Abdalla (1999)

If properly managed, the resulting holistic understanding facilitates the early detection of potential problems and helps expose complex or fuzzy interdependencies. CE encourages multidisciplinary collaboration, and increases the efficiency of product development and marketing. CE pays attention to down-the-line activities (manufacturing, operation, maintenance, and decommissioning) while performing upstream activities

302 Quan, W. & Jianmin, H., A Study on Collaborative Mechanism for Product Design in Distributed Concurrent Engineering IEEE 2006. DOI: 10.1109/CAIDCD.2006.329445
303 Stark, J. (1998), "Few Words about Concurrent Engineering" [Online] Assessed on 8 October 2016, from www.johnstark.com/fwcce.html
304 Sofuoglu, E. (2013), "Different Approaches to Concurrent Engineering" [Online], Assessed on 12 October 2016, from www.cerc.wvu.edu
305 Hartley, J. (1992),"Concurrent Engineering. Shortening Lead Times, Raising Quality and Lowering Costs" Productivity Press, Cambridge, The UK

(conception, specification, and design). Thus, through teamwork and the collaboration between relevant stakeholders, several competitive advantages are obtained:

1. Product cycle **time reduction.** [306]
2. End-product **cost reduction**.[304]
3. **Enhanced quality** of the product: quality must be designed into the product, not inspected into it. [307]
4. Life-cycle **environmental impact reduction** (less time, space, materials, energy…). [308]
5. **Increased motivation** of the workers involved in the process through team work and engagement. [309]
6. Higher **satisfaction** of all stakeholders via quality function deployment. [310,311]

All this makes the implementation of CE a competitive advantage for companies. Indeed, in sectors where clients value time reduction, fast-cycle developers have a specific advantage. Besides, in highly technological sectors such as telecommunications and electronics, where technology performance of the product increases and prices drop constantly, the competitive edge preservation strongly derives from a continuous introduction of novel or enhanced technologies and products. The time parameter increasingly breaks the difference between mere survival and important profit. Concurrent engineering meets this need, enabling a firm to be responsive to the demands of the customer to ensure their satisfaction.

The two major factors hindering the successful adoption of concurrent engineering are organizational and technical barriers. Computer models are often required to be exchanged efficiently, which is complex. Were these issues not faced properly, concurrent design would not work properly[312]. For concurrent engineering to succeed, effective introduction of tools, techniques, and technologies that aid the integration of people and processes smoothly is essential. Tools, methods and knowledge of simulation of SoS in the FoF are thus essential enablers for the future of Concurrent Engineering.

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[306] Sandip, B., Nabarun B., Supriya N.B. and Sweta S. (2013) A Study of Concurrent EngineeringBased Design and Product Development. International Journal of Recent Advances in Mechanical Engineering (IJMECH); Vol. 2 No. 1, pp. 15- 20

[307] Autotec (2017), “Five Benefits of Concurrent Engineering” [Online] assessed on 30 May 2017, from http://news.aucotec.com/5-benefits-concurrentengineering

[308] Stjepandic, J., Verhagen, W. and Wognum, N. (2015), “CE Challenges – Work to Do” Accessed on 2 June 2017, from: https://www.researchgate.net/publication/280086556_ CE_Challenges_-_Work_to_Do

[309] Jain, K., and Aggarwal, L. (2009), “Production Planning Control and Industrial Management”Khanna Publishers, Darya Ganj, New Delhi, India

[310] Akao, Y. (1990),An Introduction to Quality Function Development. Quality Function Development (QFD); Integrating Customer Requirement into Product Design. Productivity Press, Cambridge, Massachusetts; pp.1-24

[311] Nabozniak, R. (2017), “Five Benefits of Concurrent Engineering for Manufacturers” [Online] Assessed on 30 May 2017 from https://www.plantengineering.com/single-article/fivebenefits-of-concurrent-engineering-formanufacturers/8bf7687f3ee7a9913930b2a1dd524c72 .html

[312] Rosenblatt, A. and Watson, G. (1991). "Concurrent Engineering", IEEE Spectrum, July, pp 22-37.

In conclusion, concurrent engineering is an effective workflow methodology if properly implemented that will improve product quality and the objectives of the factory. Nonetheless, as every company and product is different, the procedures and methods cannot be homogeous. Thus, customising an adapted system in place across the People/Processes/Technologies is vital to the success and a hardships addressed by product managers.

5.1.2. Virtual Commissioning (VC)

Virtual Commissioning refers to the use of a virtual simulation to blueprint, evaluate or install (commissioning) control software prior to the integration into a real system thanks to a virtual machine model. It implies the prompt validation and development of programmable logic controller (PLC) code by the means of a simulation model. In logistic it is used for simulation of processes and validation of automation system[313, 314, 315]. A digital twin (DT) is managed by the code of the PLC programm, allowing for its optimisation and validation previous to the real commissioning[316]. The adoption of Virtual Commissioning is increased since software components become increasingly relevant[317].

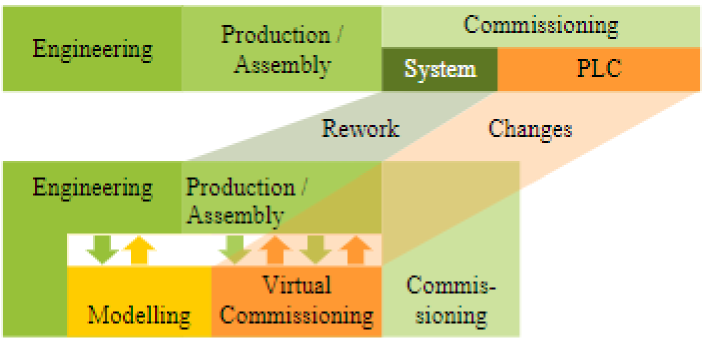

Figure 42: Engineering with and without VC[318]

The figure above presents the effect of virtual commissioning in the engineering process. To start, the modelling of the production system allows the identification of errors and discrepancies in the construction[319]. Since VC is done simultaneously to the production

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[313] Hofmann W, Langer S, Lang S, Reggelin T. Integrating Virtual Commissioning Based on High Level Emulation into Logistics Education. Procedia Engineering 2017;178:24–32.
[314] Kim YS, Shin KY, Lee JH, Lee SS, Kim KS, Kang KC et al. Application of virtual commissioning technology in a steel making industry. 2013 13th International Conference on Control, Automation and Systems (ICCAS 2013) 2013.
[315] Vilacoba D, Weber P, Pérez P, Gracia A. Optimized Press Line Orchestration through Virtual Prototyping: A successful story. IEEE International Conference on Industrial Technology (ICIT) 2016
[316] Thapa D, Mok Park C, Dangol S, Wang G. III-Phase Verification and Validation of IEC Standard Programmable Logic Controller: CIMCA 2006/IAWTIC 2006 ; Nov. 28, 2006 - Dec. 1, 2006, Sydney, NSW, Australia 2006.
[317] Wünsch G. Methoden für die virtuelle Inbetriebnahme automatisierter Produktionssysteme. München: Utz; 2008
[318] Zäh M. F., Wünsch G., Hensel T., Linworsky A. Feldstudie - Virtuelle Inbetriebnahme. Werkstattstechnik 2006
[319] Auris F, Süß S, Schalg A, Diedrich C. Towards shorter validation cycles by considering mechatronic component behaviour in early design stages 2017

and assembly process, the optimisation of loops (the arrows in the figure) saves critical time in the following commissioning process. Additionally, it enables a safer process by solving detected problems before the real commissioning.[320]

Each virtual commissioning operation is based on a virtual model connected to the PLC, with the PLC being able to be a real hardware controller or an emulated one (Hardware in the Loop, HiL VS Software In the Loop, SiL)[321]. The former allows to perform VC with a PLC built later into the production system, the later requires no instrumentation PLC. Moreover, a reality in loop simulation can be done, by integrating an emulated PLC in the production system in order to test certain real components[322]. As for the virtual model, integration with components of the real machine is possible to test their future function, obtaining a hybrid simulation. Moreover, VC can be introduced in various software tools, each with their advantages in terms of performance, reliability and ease of use; a careful comparison of these must be done in the near future.

The implementation of virtual commissioning into the current engineering processes is challenging for multiple causes, namely the high start-up costs of implementation as well as the high overall complexity.[323] Most of these complications are due to the modelling process[11], and to improve it, there are various methods. First, research nowadays centres around the automated generation of VC models[324], so an adequate abstraction is assessed in relation to the simulation model[325]. Aside from that, VC models reutilisation benefits from advanced standardization of components of production systems[326]. Using the final behaviour model, the basic conduct of the production system can be verified in collisions and poor designs.

Among the major benefits of a VC is the ability to check the planned cycle time of a manufacturing system[327]. Moreover, scenarios that could lead to expensive accidents in real life can be tested: this is performed by manually manipulating the simulated

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320 Brökelmann J. Systematik der virtuellen Inbetriebnahme von automatisierten Produktionssystemen. Zugl.: Paderborn, Universität Paderborn, Diss., 2014. Paderborn.
321 Oppelt M, wolf G, Urbas L. Towards an integrated use of simulation within the life-cycle of a process plant: 8 - 11 Sept. 2015, City of Luxembourg, Luxembourg 2015.
322 Lee CG, Park SC. Survey on the virtual commissioning of manufacturing systems. Journal of Computational Design and Engineering 2014;1(3):213–22.
323 Drath R, Weber P, Mauser N. An evolutionary approach for the industrial introduction of virtual commissioning. In: ETFA 2008, p. 5–8.
324 Prat S, Cavron J, Kesraoui D, Rauffet P, Berruet P, Bignon A. An Automated Generation Approach of Simulation Models for Checking Control/Monitoring System.
325 Jia Q-S (ed.). Towards Finding the Appropriate Level of Abstraction to Model and Verify Automated Production Systems in Discrete Event Simulation. Piscataway, NJ: IEEE; 2015.
326 Oppelt LU M. Integrated Virtual Commissioning an essential Activity in the Automation Engineering Process: From virtual commissioning to simulation supported engineering. In: IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society.
327 Philippot A, Riera B, Kunreddy V, Debernard S. Advanced tools for the control engineer in Industry 4.0. In: 2018 IEEE Industrial Cyber-Physical Systems (ICPS). IEEE; 2018 - 2018, p. 555–560.

environment. Nowadays research studies the automated formation of test cases resulting from the structure of production systems.[328]

Most of VC applications focus on the automation level. Consequently, most applications demonstrate functionality using demonstrative test beds. Logistics applications are shown only at the level of automation. In the fields of robotics, there are many applications that focus mainly on assembly in relation to handling operations; the rare process-related use cases are in the manufacturing as well as in test environments. In general, the examples presented show that VC simulation is used in a wide area of application, although its potential is not fully exploited.[329]

5.1.3. Digital Lean Production (D-Lean)

Lean Manufacturing (LM) is a meticulous approach to waste minimisation along the production process. It is a toolbox that helps in the identification and elimination of waste. This makes quality improve through a deep understanding of the customer's needs while reducing production time and cost[330]. Conventionally, seven types of waste exist for lean philosophy within the physical world: defects, overproduction, waiting, transportation, motion, inventory and over-processing, to which one was added: not using talent[331]. Digital Lean Manufacturing (DLM) does not subvert the former principles. On the contrary, it draws from new data management and visualization capabilities[332] to form diverse descriptive, predictive and prescriptive analytics applications[333]. These novel digital/smart manufacturing (D/SM) technologies[334, 335] (eg Big Data, IIoT and advanced analysis) assist to better detect and tackle the traditional 7+1 forms of physical waste[336]. Thus, established lean methods help gaining new digitally enabled advantages [337], obtaining increased productivity and production levels, greater quality and an optimal use of resources.[338]

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[328] Süß S, Magnus S, Thron M, Zipper H, Odefey U, Fäßler V et al. Test methodology for virtual commissioning based on behaviour simulation of production systems: September 6-9, 2016 Berlin, Germany 2016
[329] Drath R, Weber P, Mauser N. An evolutionary approach for the industrial introduction of virtual commissioning. In: ETFA 2008, p. 5–8.
[330] Bicheno J., Holweg, M.: The Lean Toolbox: The Essential Guide to Lean Transformation. Buckingham: PICSIE Books (2009)
[331] Liker, J.K.: The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer. McGraw-Hill, New York (2004)
[332] Kusiak, A.: Smart Manufacturing Must Embrace Big Data. Nature, 544(7648):23-25 (2017)
[333] Wuest, T., et al.: Machine Learning in Manufacturing: Advances, Challenges, and Applications. Production & Manufacturing Research, 4(1):23-45 (2016)
[334] Sameer, M., Muztoba, K., Romero, D., Wuest, T.: Smart Manufacturing: Characteristics, Technologies and Enabling Factors. J. of Engineering Manufacture (2017)
[335] Mora, E., Gaiardelli, P., Resta, B., Powell, D.: Exploiting Lean Benefits through Smart Manufacturing: A Comprehensive Perspective. Part I, IFIP AICT 51:127-134 (2017)
[336] Kolberg, D., Zühlke, D.: Lean Automation Enabled by Industry 4.0 Technologies. IFAC Symposium on Information Control Problems in Manufacturing, 48(3):1870-1875 (2015)
[337] Behrendt, A., et al.: Industry 4.0 Demystified - Lean's Next Level. McKinsey & Co. (2017)
[338] Romero D., Gaiardelli P., Powell D., Wuest T., Thürer M. (2018) Digital Lean Cyber-Physical Production Systems: The Emergence of Digital Lean Manufacturing and the Significance of Digital Waste. In: Moon I., Lee G., Park J., Kiritsis D., von Cieminski G. (eds) Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing. APMS 2018. IFIP Advances in Information and Communication Technology, vol 535. Springer, Cham

DLM introduces novel information and operational technologies, (i.e. robust virtual models/simulations and real-time performance supervision programme) with the capacity to proactively identify and remove physical waste in production systems[338]. Nonetheless, diverse types of digital waste emerge as physical production systems evolve to cyber-physical ones. This covers redundant or not-needed data collected, managed, transmitted or stored without explicit reasons and that generate wasteful data congestion in the process[339].

Waste is seen in lean manufacturing as 'any non-value adding activity'[340, 341], and Digital waste is therefore any digital activity that does not add value to (wo)men, materials, machines, methods and measurements (5M)[338]. New techniques are needed to identify and eliminate digital waste, where two different types arise[342]:

i. passive digital waste caused by skipping digital opportunities that would exploit the usability of (existing) data, and

ii. active digital waste caused by an improper information management that fails to provide the information needed for the accurate execution. This is common in manufacturing processes where data is abundant but where the precise amount of information, at the right time to the needed person, machine or system is not sent.

Thus, D-Lean Cyber-Physical Production Systems allow to run smart factories towards (near) zero physical and digital waste. This can be reached by a synchronised production system[343] (ie. digital twins[344]) between virtual models and simulations[345] that will help to design, engineer, verify and validate waste-free manufacturing virtually before the implementation in the real FoF. This will also enable the evaluation of real-time performances in the manufacturing process to monitor if the optimal levels of productivity, efficiency and quality is obtained, or if there remain opportunities for improvement *(Kaizen).*

Additionally, D/SM technology and vertical and horizontal factory data integration[346] will contribute to minimize waste in the process of creating *digital lean capabilities* such as:

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339 Loshin, D.: Business Intelligence and Information Exploitation. Business Intelligence, Second Edition, Chapter 1, pp. 1-13, Morgan Kaufmann Publishers, USA (2012)
340 Thürer, M., Tomašević, I., Stevenson, M.: On the Meaning of 'Waste': Review and Definition, Production Planning & Control, 28(3):244-255 (2017)
341 Tamás, P., Illés, B., Dobos, P.: Waste Reduction Possibilities for Manufacturing Systems in the Industry 4.0. 20th Innovative Manufacturing Engineering and Energy Conference (2016)
342 Romero D., Gaiardelli P., Powell D., Wuest T., Thürer M. (2018) Digital Lean Cyber-Physical Production Systems: The Emergence of Digital Lean Manufacturing and the Significance of Digital Waste. In: Moon I., Lee G., Park J., Kiritsis D., von Cieminski G. (eds) Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing. APMS 2018. IFIP Advances in Information and Communication Technology, vol 535. Springer, Cham
343 Stjepandic, J., Wekerle, T., Pfouga, A.: Advancing Smart Factories with Synced Factory Twins Approach: Representation and Scenarios for Synchronized Digital and Real Factories. Symposium on Tools and Methods of Competitive Engineering (2018)
344 Tao, F., et al.: Digital Twin-driven Product Design, Manufacturing and Service with Big Data. Int'l. J. of Advanced Manufacturing Technology (2017)
345 Pedrazzoli, P., Sacco, M., Jönsson, A., Boër, C.: Virtual Factory Framework: Key Enabler for Future Manufacturing. Digital Enterprise Technology, pp. 83-90 (2007)
346 Santos, M.Y., et al.: A Big Data Analytics Architecture for Industry 4.0. Recent Advances in Information Systems and Technologies, Vol. 570, Springer (2017)

(1) data visualisation (e.g. dashboards…),

(2) information transparency (e.g. real-time production monitoring and communication systems), and

(3) (critical) events forecasting of production operations conducted by humans, machines and computer systems on the shopfloor (e.g. predictability charts for continues improvement).

To summarise, Industry 4.0 presents manufacturing enterprises with a plethora of new technologies[347] that promise greater competitiveness through higher quality, lower cost, and shorter lead-times. However, following the true spirit of Lean Manufacturing and European values, firms should not neglect the power of the respect-for-people pillar, even though the promise of automation is extremely attractive. Indeed, new (smart) digital technologies can help to develop greater levels of human creativity, ingenuity and innovation.[348]

5.1.4. Total Quality Management (TQM)

In manufacturing, "quality" is defined as a measure of excellence or a state of being free from defects, deficiencies and significant variations. ISO 9000:2015 defines quality as the "degree to which a set of inherent characteristics of an object (product, service, process, person, organization, system, resource) fulfils requirements (need or expectation that is stated, generally implied or obligatory)".[349]

The definition shows that the concept of quality in manufacturing can be declined according to the object of interest. The attention is focused both on the product or parts, processes and machines. Product quality can be defined as the overall conformity of a manufactured product to specifications and requirements from the end user. In other words, product quality looks at how much the product features and functionalities satisfy the end user's expectations. On the other hand, process quality focuses on the manufacturing activities required to manufacture a product and it is about ensuring that it is "fit for purpose".

The concept of quality evolved over years from the mere consideration of the product to a broader concept of Total Quality Management (see Figure 43). The first step in the quality evolution was characterized by a simple inspection (I) performed by an operator at the end of the production process with a go/no-go approach and, if needed, some corrective actions were implemented. Then quality control (QC) and then quality assurance (QA) started to be performed. They consist in the development and use of quality manuals, quality planning and statistical approach, which implies measuring, analysing and monitoring product quality parameters in a systematic way. The aim is to spot deviation

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347 Mittal, S., Kahn, M., Romero, D., Wuest, T.: Smart Manufacturing: Characteristics, Technologies and Enabling Factors. Part B: Journal of Engineering Manufacture, pp. 1-20, DOI 10.1177/0954405417736547 (2017)

348 Romero D., Gaiardelli P., Powell D., Wuest T., Thürer M. (2019) Total Quality Management and Quality Circles in the Digital Lean Manufacturing World. In: Ameri F., Stecke K., von Cieminski G., Kiritsis D. (eds) Advances in Production Management Systems. Production Management for the Factory of the Future. APMS 2019. IFIP Advances in Information and Communication Technology, vol 566. Springer, Cham

349 https://www.iso.org/obp/ui/#iso:std:iso:9000:ed-4:v1:en

from the desired values and put in place preventive action reducing costs, related to rework, waste, and mayor stoppages. Following these objectives, quality management practices as Total Quality Management (TQM) were introduced.

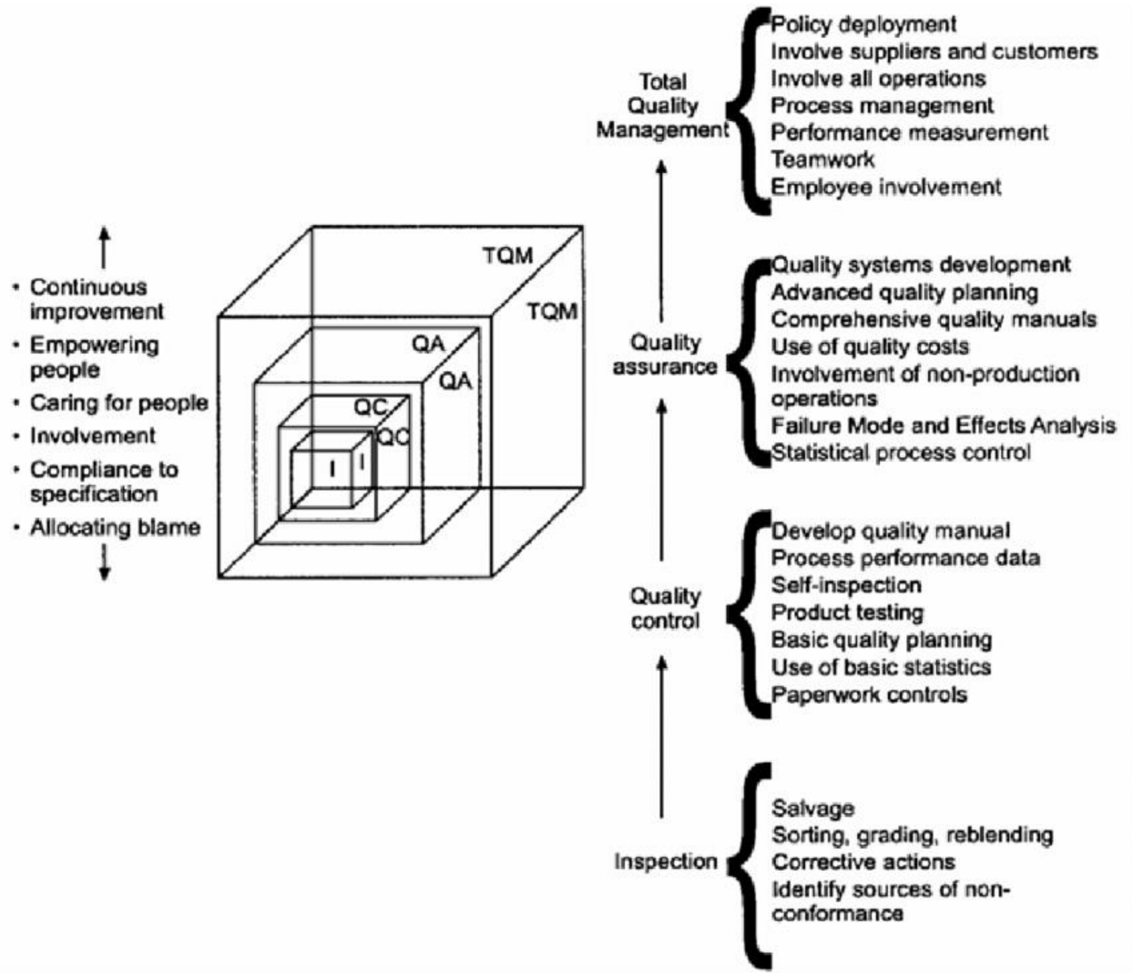

Figure 43: Evolution of quality management ISO 9000[350]

Total Quality Management is therefore a managerial approach, focused on quality and based on the participation of all members of an organization. The goal is to achieve long-term success through customer satisfaction and benefits that bring advantages to workers and society. All members of an organization participate in continually improving processes, products, services, and the culture in which they work.

Considering product quality, this means to monitor and assure quality of the product from ideation to use. In the design phase, before production, customers' needs must be identified and included in the product specifications. Then, during the production, quality must be monitored at different stages and finally after production quality controls must be performed to check conformity with design-specification. TQM uses strategy, data, and

[350] Jamshidian, M., & Shahin, A. (2004, July). ISO 9000 or total quality management: which one first?. In *The Proceeding of the 5th Quality Managers Conference* (pp. 4-7).

effective communications to integrate the quality discipline into the culture and activities of the organization. Here are the 8 principles of total quality management[351]:

1. **Customer-focused:** The customer ultimately determines the level of quality. No matter what an organization does to foster quality improvement—training employees, integrating quality into the design process, or upgrading computers or software—the customer determines whether the efforts were worthwhile.
2. **Total employee involvement:** All employees participate in working toward common goals. Total employee commitment can only be obtained after fear has been driven from the workplace, when empowerment has occurred, and when management has provided the proper environment. High-performance work systems integrate continuous improvement efforts with normal business operations. Self-managed work teams are one form of empowerment.
3. **Process-centred:** A fundamental part of TQM is a focus on process thinking. A process is a series of steps that take inputs from suppliers (internal or external) and transforms them into outputs that are delivered to customers (internal or external). The steps required to carry out the process are defined, and performance measures are continuously monitored in order to detect unexpected variation.
4. **Integrated system:** Although an organization may consist of many different functional specialties often organized into vertically structured departments, it is the horizontal processes interconnecting these functions that are the focus of TQM.
5. **Strategic and systematic approach:** A critical part of the management of quality is the strategic and systematic approach to achieving an organization's vision, mission, and goals. This process includes the formulation of a strategic plan that integrates quality as a core component.
6. **Continual improvement:** A large aspect of TQM is continual process improvement. This drives an organization to be both analytical and creative in finding ways to become more competitive and more effective at meeting stakeholder expectations.
7. **Fact-based decision making:** In order to know how well an organization is performing, data on performance measures are necessary. TQM requires that an organization continually collect and analyse data in order to improve decision making accuracy, achieve consensus, and allow prediction based on past history.
8. **Communications:** During times of organizational change, as well as part of day-to-day operation, effective communications plays a large part in maintaining morale and in motivating employees at all levels. Communications involve strategies, method, and timeliness.

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[351] https://asq.org/quality-resources/total-quality-management#:~:text=A%20core%20definition%20of%20total,culture%20in%20which%20they%20work.

In the 21st century, starting from TQM, holistic frameworks aimed at helping organizations to achieve excellent performances especially in customer satisfaction and business betterments were developed.

5.1.5. Autonomous Quality (AQ)

Quality control, as well as all the other manufacturing process, are subject to the Fourth Industrial Revolution that has being transforming how the manufacturing and industrial processes are performed by introducing a high degree of digitalization. Advanced manufacturing systems are now changed into "Smart manufacturing" to define "a data intensive application of information technology at the shop floor level and above to enable intelligent, efficient and responsive operations[352] by use of data analytics.

"Autonomous" in manufacturing can be defined as the ability of a system to gain information about the environment in which it operates, learn and take decisions in order to adapt itself to a specific situation without the need of human intervention or working in a collaborative way with humans to augment or complement their activities.

In that light, Autonomous Quality (AQ) can be defined as a real-time quality control process supported by Industry 4.0 enabling technologies where, at the maximum level of system autonomy, the decisions (closing loop) are taken by software after a deep data analysis[353,354]. On the other hand, we have to distinguish between AI and Machine Learning. AI means that machine can perform tasks in ways that are "intelligent" adapting to different situations. Machine Learning is in this context based on the idea that can build machines to process data and learn on their own, without our constant supervision

Autonomous Quality is intended as a paradigm for ZDM in the Factories of the Futures (FoF), which requires the implementation of interrelated control loops for real-time adaptation, flexible composition, smart planning and continuous learning.

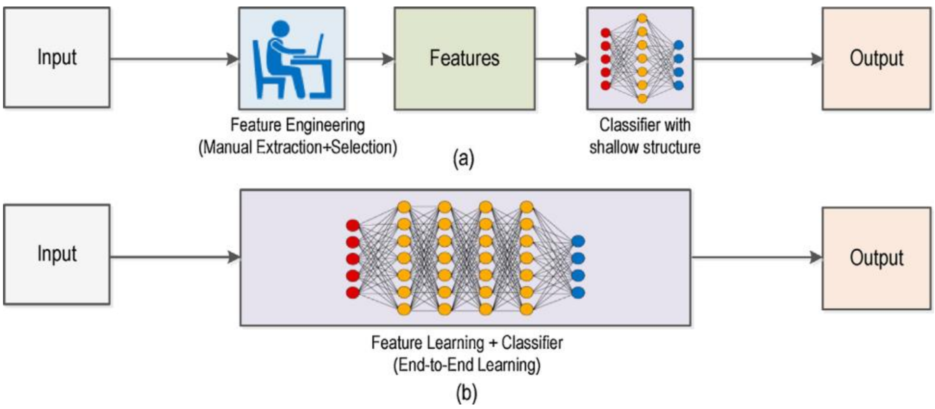

Figure 44: Comparison between two techniques: a) traditional machine learning. b) deep learning[354]

[352] E. Wallace and F. Riddick, ""Panel on Enabling Smart Manufacturing"," in APMS, Washington, US, 2013.
[353] J. Lenz, T. Wuest and E. Westkämper, "Holistic approach to machine tool data analytics," *Jornal of Manufacturing System,* pp. 180-191, 2018.
[354] J. Wang, Y. Ma, Z. Laibin and X. G. Robert, "Deep learning for smart manufacturing: Methods and applications," *Journal of smart manufacturing: Methods and applications,* pp. 144-156, 2018.

The EC is now on the forefront in promoting the concept of the AQ. The evolution of ZDM in Industry 4.0 systems is characterized by a four-steps pathway[355].

- Descriptive purpose: the goal is to describe the current status / what it is happening of the element under analysis
- Diagnostic purpose: the goal is to understand why something is happening
- Predictive purpose: the goal is to understand what likely will happen
- Prescriptive purpose: the goal is to recommend what should be done, provide guidelines/improvement action to reach the desired status

In that light, the AQ aims at reducing the human input in the data analysis and process control to achieve the automation of the loops of information through improved use of more complex control systems. The goal is to achieve autonomous decision-making processes to assure the quality of production processes and related output in autonomous way. The figure below explains in a generic way the path to achieve AQ in Industry 4.0 systems provided by Philips and their approach to define the pilot[356].

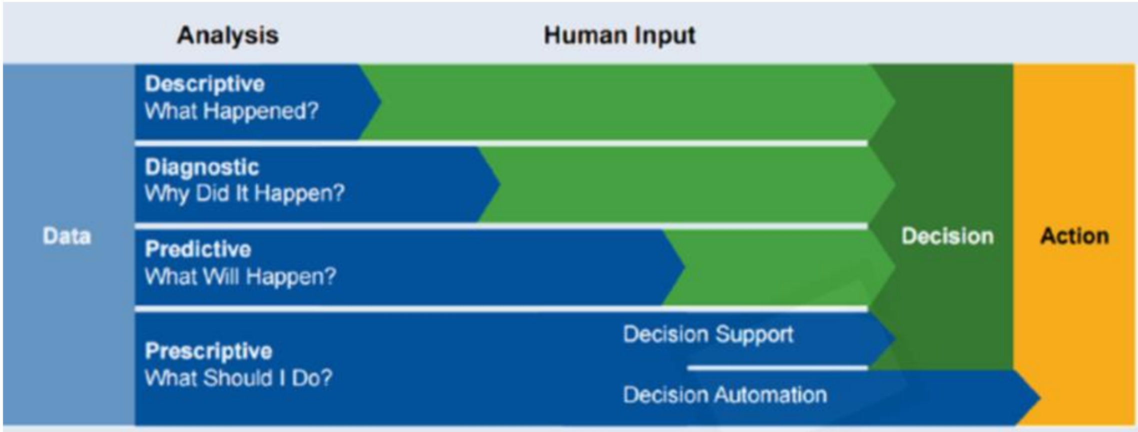

Figure 45 Types of analytic capabilities (current state: descriptive/diagnostic)

Therefore, in order to realise an AQ paradigm, four types of control loops are required[357]:

- real-time control loop – it is a control system where the time window to collect and process data to then update the system is tight. If there is not a defined time window, the system stability is in danger.
- composition & orchestration control loop – the data collected must be integrated to support the decision system, the orchestrator automates sequences of activities by implementing the necessary rules and policies in order to change the system state in response to an event.

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[355] F. Psarommatis, G. May, P. Dreyfus and D. Kiritsis, "Zero defect manufacturing: state-of-the-art review, shortcomings and future directions in research," International Journal of Production Reserach, p. 20, 2019.
[356] https://www.gartner.com/en/doc/344077-accelerating-digitalization-in-manufacturing-industries-primer-for-2018
[357] Industrie 4.0 and VDI/VDE, "Working paper - Exemplification of the industrie 4.0 Applcation Scenario Value-Based Service following IIRA Structure," BMWI, DE, 2017.

- deep control loop – the data mining infrastructure will support deep-learning as a means of providing AI capabilities in manufacturing analytics. Existing data analytics infrastructures that are already customized for manufacturing (i.e. listed in Section 1.3) will be used to accelerate the developments.
- augmented human in the control loop – the availability of new technologies that allow data handling and visualization using mobile/wearable apps (mobile middleware) contribute to keeping the human in the loop while reducing errors[358].

[358] W. D. Nothwang, M. Robinson and A. Samuel, "The Human Should be Part of the Control Loop?," 2016.

5.2. Commercial solutions for Factory SoS Simulation

5.2.1. M3 Dimensional Quality Control Simulation

The M3 platform is poised to provide a structured solution for Metrology4.0, an edge-powered quality control analytics, monitoring and simulation system. This solution is used for the organization, analysis and reporting operations of the metrological information, taking advantage of the storage and computational capabilities of the cloud to carry out advanced operations and provide smart added value services

5.2.1.1. Capabilities for Industry 4.0

This solution is used for the organization, analysis and reporting operations of the metrological information, taking advantage of the storage and computational capabilities of the cloud to carry out advanced operations and provide smart added value services. Figure 34 depicts the M3 global architecture. Within the range of the proposed framework, M3 Software, M3 Workspace and M3 Analytics will be adapted, extended and implemented to serve the purpose of the pilot.

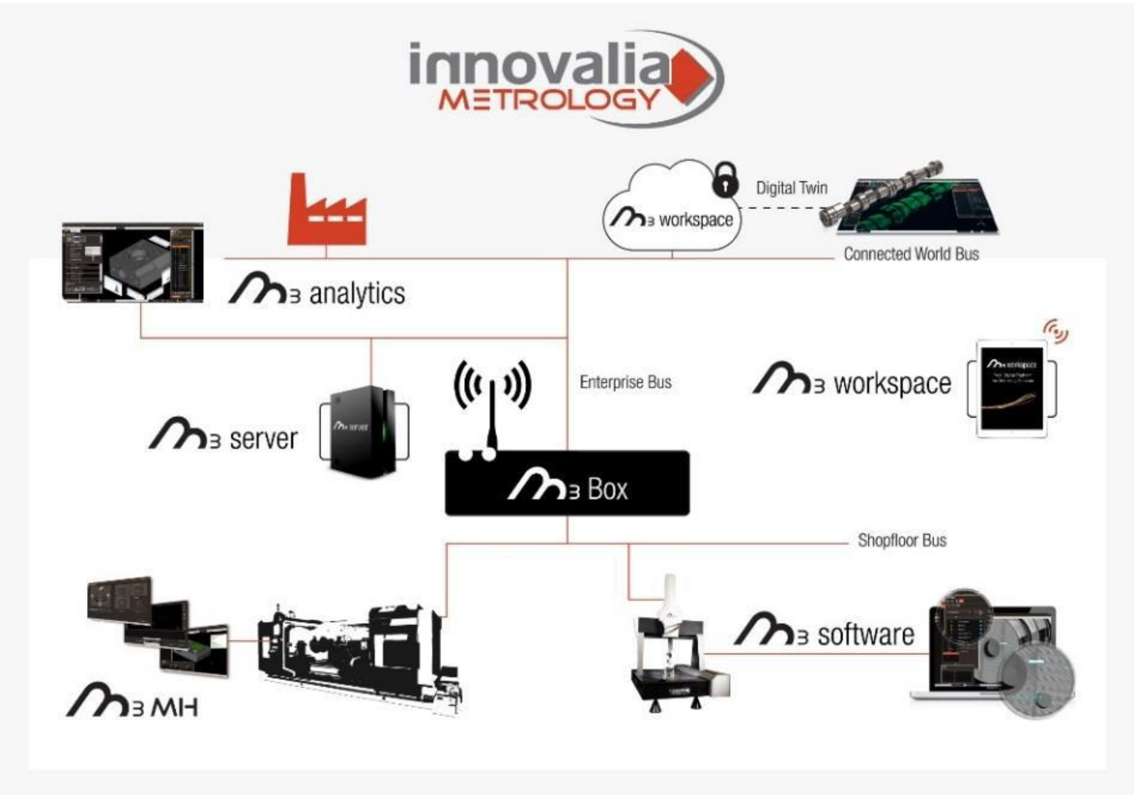

Figure 46: M3 architecture

M3 Software

The M3 software is a high-performance software for capturing and analysing point clouds. This module allows to scan and to capture point clouds of the real pieces, in a versatile, agile and powerful way. The M3 software in combination with the 3D optical scanners can be used to develop precise and highly accurate point cloud images that can then be converted to different 3D design and modelling software. These scanned images can then be cross referenced with the original designs or with other scanned objects allowing for quick and accurate comparison and discovery of deformation or other dimensional discrepancies. The M3 software covers the entire spectrum of metrology, regardless of device, brand or model. It works locally but is powered up by the use of the edge-powered technologies included in the global solution.

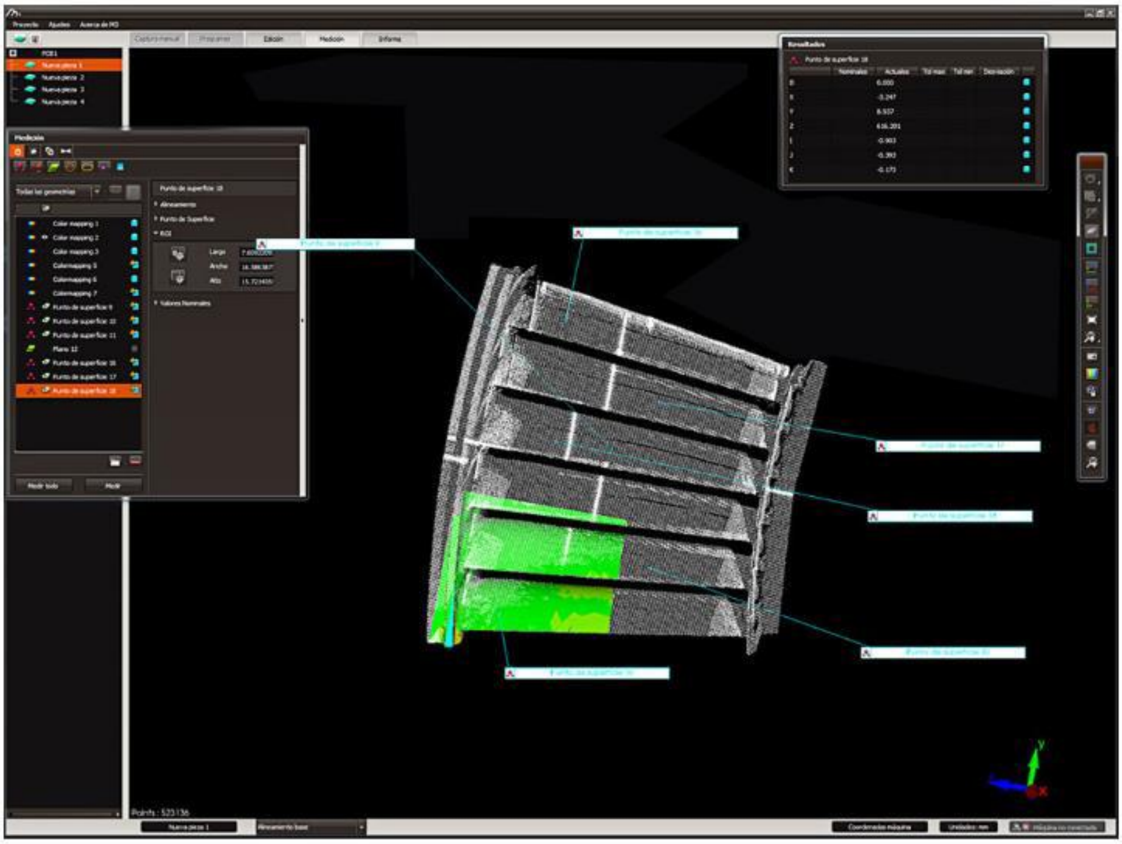

Figure 47: M3 software

M3 Analytics

The M3 analytics is a powerful tool that enables the visualization, the statistical analysis and the reporting operations related to all the data stored in the cloud by means of several algorithms and computational components. As this tool makes use of the memory and computational resources available in the cloud, it is possible to use it anytime and anywhere and by means of a simple computer or tablet with low computational capacities. Its main features are:

- Create control Dashboards
- Combine production data with measurement data
- Automation of reports
- Histograms
- Cp and Cpk Ctatistics
- Custom Filters

M3 Workspace

M3 Workspace is a cloud-based metrology software that synchronizes with the main M3 Metrology software which allows for the automated uploading of any metrology results straight to the cloud. M3 workspace is web based and allows users with access to visualize the results (Point clouds, CAD models, Color mapping, Reports, etc.) using any smart device. In addition, M3 Workspace acts as a sort of repository where all the results that come from the measurements are located and can then be easily downloaded for further analysis. It permits the massive management of digital parts and point clouds, storing and sharing the metrological information.

5.2.1.2. Open APIs & Interfaciong

The objective is to optimise the speed of data acquisition, visualization and processing for massive metrological data and to design and create a collaborative predictive analytics platform to make decision making data savvy. Therefore, in the end, the overall efficiency of production process will be increased.

In this context, two different Data Owners can be defined:

- TRIMEK: provides, processes and analyses metrological data from different sources.
- Owner of the production system: provides production data and quality data related to different products.

The use of the IDS connector at the factory brings the necessary warranty to TRIMEK that only the measurements and processed data which have been approved can be delivered to the predictive quality control solution. Likewise, owner of the production system will be sure that only the relevant product and process data is going to be delivered and published.

TRIMEK is deploying and configuring a M3 FIWARE System Adapter in the IDS Connector. Thus, the metrological data coming from the Coordinate Measuring Machines (CMMs) is sent to the M3 Platform to analyse the performance of the CMM and ensure zero defects. Likewise, the IDS-ready connector could also send product quality measurements and process information to the predictive quality control solution, enabling advanced analysis for zero defects and zero breakdowns.

In short, only TRIMEK will be able to exchange data with the owner of the process and be certified to request specific data under data owner's usage policy. The terms and conditions of the Data sovereignty will be detailed throughout the development of the project.

5.2.1.3. Scope

M3 solution will be extended and adapted for its implementation for data management, data integration, data visualization and data analysis for an anthropomorphic arm:

- **Rapid transmission and processing solution of metrological data**: The **M3 Software** will permit to transmit and process data from different sensors almost in real time so as to minimise latency and improve the decision-making process.
- **High-performance massive point clouds processing and visualisation**. Manufacturing processes in FoF require levels of dimension and complexity that

need powerful processing software to render massive 3D point clouds and realistic colour maps with texture. The M3 software meets this processing power with new algorithms designed to realise texture mapping for complex parts and the implementation of the QIF standard to cover the complete metrological process from the Product Manufacturing Information (PMI) to the analysis and reporting.

- **Cloud solution** for quality data management and storage. Current scattered metrological data will be centralised and stored in the cloud, ready to be connected and processed with production data, being accessible through user-friendly interface. The M3 Workspace will be adapted to harmonise different data formats to generate the comprehensive data processing, management and visualisation. Data will be cleaned and enriched. The M3 workspace enables the access to the quality across different systems. Moreover, processed data will also be stored in the cloud of the M3 Workspace. Finally, a connection/bridge between QIF and IDS will be developed to ensure the required interoperability.
- **Advanced data analysis** is going to be applied to the quality and production data to realise zero-defect and zero-break down production. The data gathered through production line will be transmitted to M3 Analytics module with IDS connector, the component enables the correlation of process and product data. This analysis is capable of knowledge extraction to form insightful reports to enhance process efficiency, develop trends and execute features and/or parameters comparison between process, products and similar parts across different plants, etc. M3 Analytics will be implemented to improve not only the plant's production efficiency, but also to facilitate a flexible and dynamic decision-making process.

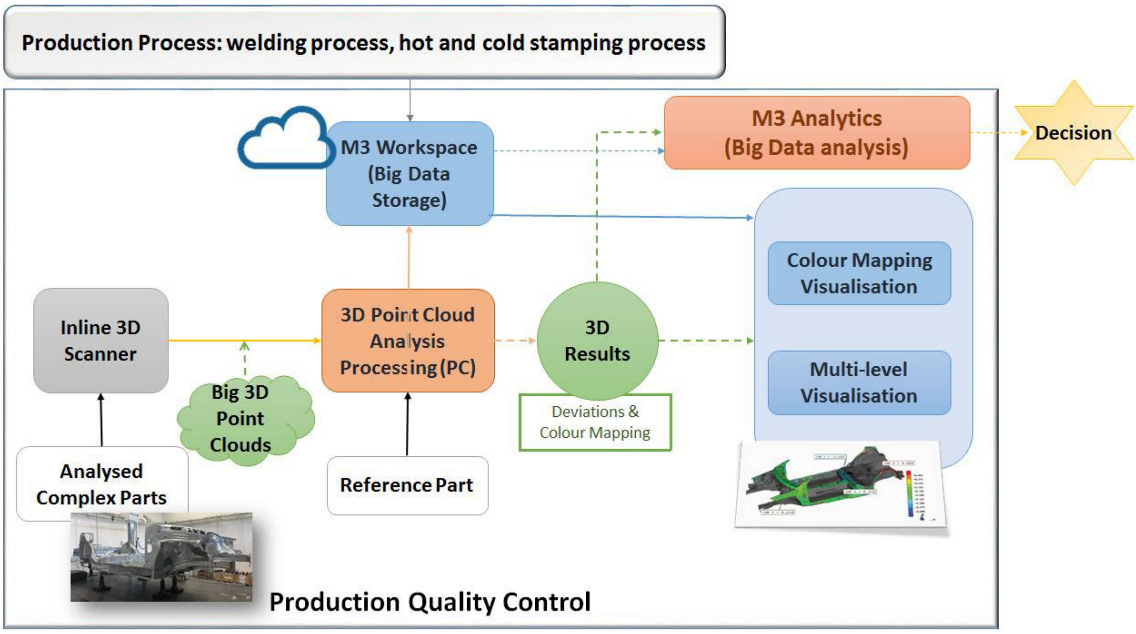

Figure 48: Example of M3 process workflow

The predictive quality control framework is going to be developed based on the M3 platform, which is poised to provide a structured solution for Metrology4.0, an edge-powered quality control analytics, monitoring and simulation system. Regarding the Big Data M3 platform, TRIMEK will extend the M3 Software, M3 Workspace and M3 Analytics in order to adapt them to fulfil the objectives of the project. In spirit of this, proper and advanced algorithms and functionalities will be implemented to cover:

- Colour mapping with textures for massive point clouds.
- Implementation of QIF standard, covering PMI.
- Harmonization of different data formats
- Collaborative cloud environment for data from different sources and locations
- Connection between QIF and IDS to ensure interoperability
- Correlation of process and product data for predictive purposes
- Knowledge extraction
- Develop trends and execute features and/or parameters comparison between process, products and similar parts across different plants, etc.

5.2.2. Visual Component 4.0

Visual Components 4.0 is a 3D Simulation and Visualization platform from Visual Components Oy, which allows create, visualize, validate, optimize and virtually commission production systems. The platform provides an intuitive interface to easily build any factory layout at different levels from a simple machine to the entire factory plant. The digital twin created in Visual Components mirrors the real factory layout to simulate and visualize all the production flows, logistics, automation and robotics.

5.2.2.1. Capabilities for Industry 4.0

Components 4.0 is a desktop 3D Simulation and Visualization platform that allows creating virtual factory layouts at different level of complexity, from a simple machine to the entire factory. The digital twin created can be interconnected with the real factory systems through the communication interface to visualize and validate production flows in the virtual environment.

The virtual layout is created using virtual components, which typically represents factory floor equipment. These components can be added from the pre-defined library provided by Visual Components (eCatalog) or created by the user from the beginning using the original CAD files. These components and their operation and interaction define the factory floor operations (see Figure below).

The Graphic User Interface of Visual Components 4.0 (Figure below) provides access through the GUI to all the necessary tools to create the factory layout, model the components, program the robotic systems, connect with external controllers and generate engineering documentation.

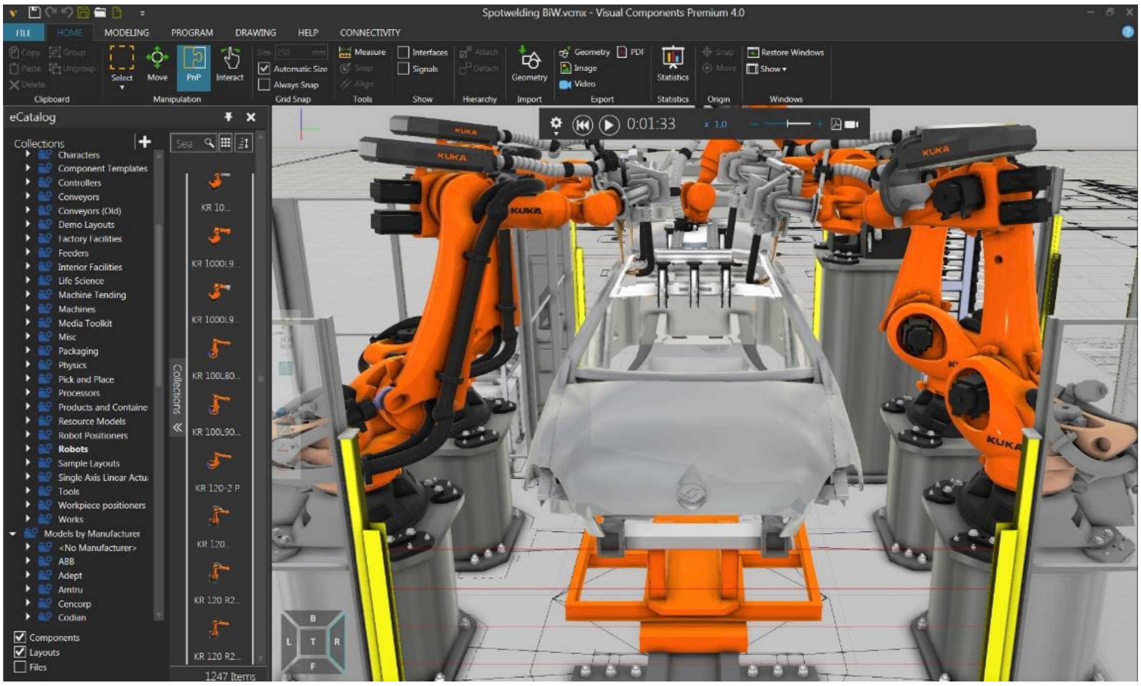

Figure 49: Visual Components 4.0 showing the GUI and the simulation of a robotic welding cell

Visual Components 4.0 is vendor independent, which allows to integrate in the same layout solutions from different vendors and arrange easily different configurations to obtain the best configuration and facilitate the deployment and commissioning of the systems in the real factory.

Visual Components 4.0 platform provides access to the different parameters of the simulated components, retrieving these parameters during the simulation allow to analyse and evaluate changes in the production during the simulation, which enables evaluating the different configurations, created in the virtual world and enhancing efficiency when configurations are transferred to the real lines.

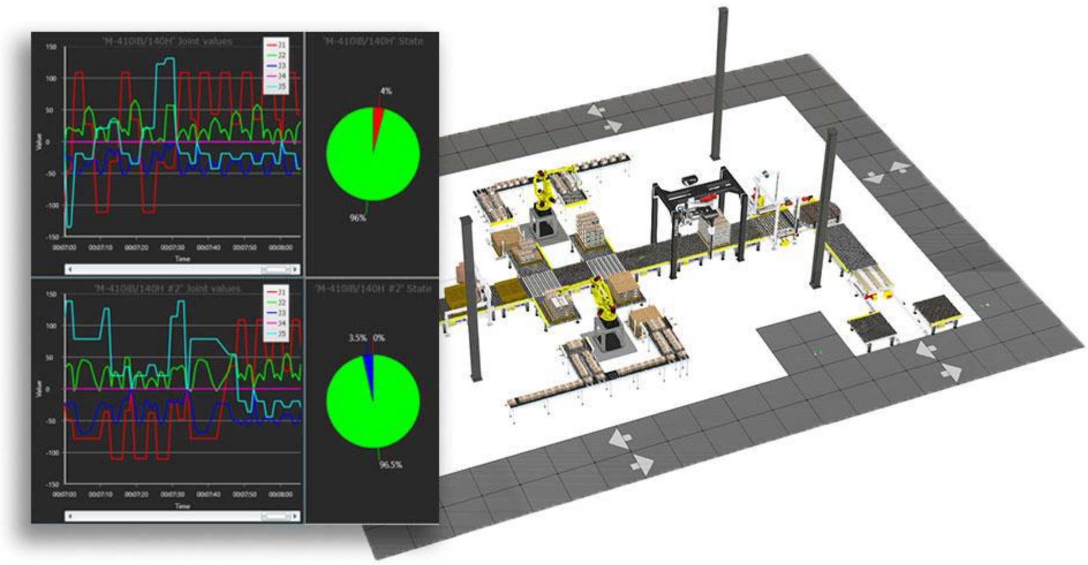
Figure 50: Screenshot of simulated factory layout and analytics obtained while virtual runtime

5.2.2.2. Open APIs & Interfaciong

Visual Components 4.0 provides two different application interfaces APIs, which allows to the users to tailor and configure its own solution, and one communication interface to interact with the simulation layout:

- Python Interface is a resource interface within our 3D simulation platform, it allows configure components and processes inside the simulation.
- .Net interface provides all the operations available in the GUI as well as access to the layout model. It is designed primarily to allow client applications to create and manipulate components and layouts.
- Communication interface allows communicating with external automation components such as robot controlers (Staubli and UR) and automation systems using OPC UA.

5.2.2.3. Scope

The Python and .Net interfaces open the possibility of creating tailored applications depending on the final user. Example of tailored applications created for Visual Components 4.0 can be found in the Visual Component's forum. [359]

Cyberfactory pilots will bring new extensions to handle big data and communicate in next to real time cases. The solutions to be developed will consider the applicability to other verticals considered inside the project, all with a system of systems approach taking into account a holistic view of the factory.

It is planned to integrate the serialization of the big data generated in the simulation into data models to be handled by AI engines. This serialization will allow introducing automatic (or semi-automatic) reconfiguration of the simulation layouts to reach maximum performance. The data generated within the simulation will be merged with historical data to improve productivity.

5.2.3. 3DEXPERIENCE (Dassault Systèmes)

While designing software a balance between development time, resources for the work, and features to implement must be achieved. Nowadays, an agile methodology advocating for continuous and flexible readjusting of decisions is the best option for optimisation. The 3DEXPERIENCE platform from Dassault Systèmes brings a diverse number of applications and infrastructure that help execute and manage systems, software and hardware lifecycle processes. It however provides open solutions to federate third-party tools into the platform, as there will always be best-in-class tools needing to be incorporated into the process.

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[359] http://forum.visualcomponents.com/forums/forum/vc40/net-addon-programming/

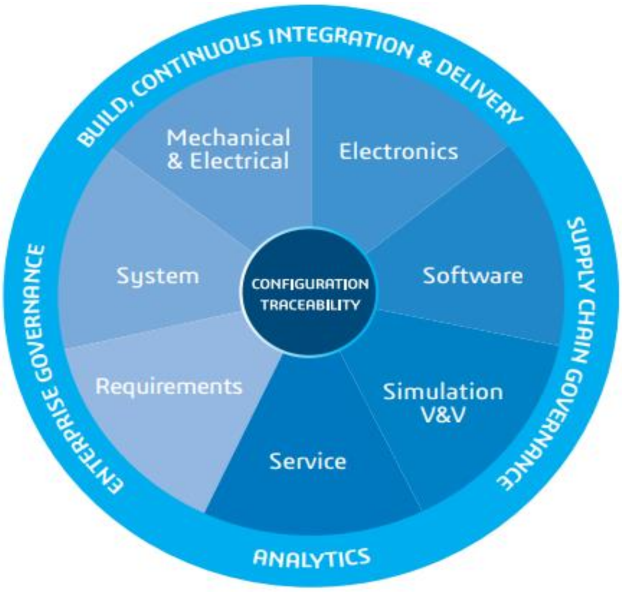

Figure 51: 3DEXPERIENCE platform to plan, build and test

5.2.3.1. Capabilities for Industry 4.0

3DEXPERIENCE® platform enables to work in flexible, efficient and quick way, employing state-of-the-art development tools (commercial, open source, etc.). In parallel, engineers monitor, control and assure the work, progress and quality while ensuring the security and protection of critical data by tracing IP (internal and external). In order for all types of multidiscipline complex products to be controlled in a flexible way, the environment handles traditional waterfall methodologies as well as agile and modular approaches. When faced with complex architectures in a regulated space, a hybrid approach is often used. The platform therefore enables the simulation of the complete virtual experience of the product with its embedded and application software, prior handling it to the end client.

While the hardware of a product is not flexible, its embedded software can be instantaneously changed, making products smarter, adaptable and customisable. In this competitive scenario, manufacturers need to manage in an ever-changing way the lifecycle of the product, from conception to disposal. This requires a holistic approach to management encompassing hardware, software and services. 3DEXPERIENCE offers a variety of views and levels of analysis depending on the point of view. R&D teams define engineering data, as well as rules for use and configuration of new versions of technological assets. Product and portfolio strategy teams explore new solution offerings. Sales and marketing teams configure specific solutions tailored to customer needs. The data model manages the hardware and software modules together and their compatibility.

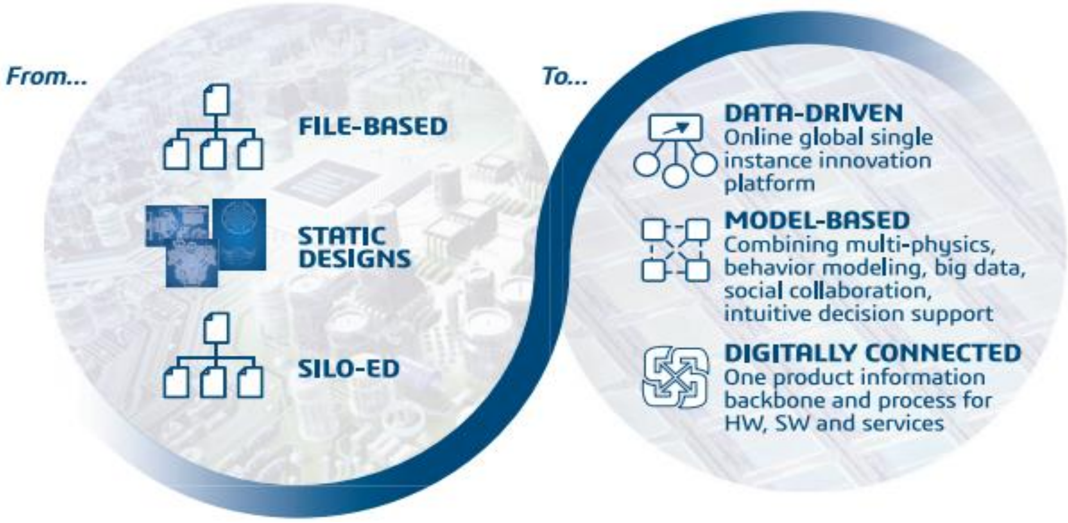

Figure 52: A data-driven, model-based and digitally connected platform

The platform unifies data in a single benchmark, allowing data-driven processes and synchronized hardware and software management. The model-based approach provides seamless integration between the different specification, design, and implementation layers, as well as full traceability (requirements for product needs, module architecture, line of code, built executables…). All this can then be tested directly with the digital twin, allowing the verification and validation of the model, software and hardware in the loop of the designed systems of systems. 3DEXPERIENCE allows the data model development and the development of a toolset for native apps, which are explained in detail next.

Dynamic Modelling. The standard schema that comes with 3DEXPERIENCE solutions can be changed or extended in a traceable way. Capabilities include the ability to define new business types, attributes, relationships, policies, workflows, organizations, people, etc.

User Interface Components and tools allow to modify the presentation and capabilities of the standard applications with minimal programming effort. These tools are access-controlled to give role-specific views and are model the entire user experience (menus, forms, tables, structure, actions, language, etc).

Definition and support of 3DEXPERIENCE Platform Specific Architecture, with concepts of "framework" and "module" to model the logical and physical architecture. APIs for Native Apps Development are provided as read-only frameworks.

Covering the full needs of an Application Developer, offering a single point of access to the C++ development tools that support the full development cycle.

Full and Seamless Integration with Microsoft Visual Studio 2012, allowing its easy use while reducing the end user learning curve.

Reduction of app development time using Generation Wizards that quickly generate reliable code. (1) With the "Component Workspace Creation Wizard" different types of frameworks and modules can be generated according to several options. (2) The "V6 Component Creation Wizard" automatically generates Interface implementation skeletons from the interface list imported by the project. (3) The "Command Creation Wizard" automatically generates command class skeletons.

Support Test and Quality control tasks critical to an efficient development, adapted for testing V6 C++ applications. Capabilities include a debug/non-debug option, variable setting for custom operations and generation of results as ASCII text or as structured xml for better integration to company processes.

Build and keep consistent any Multi-Workspace, MultiLanguage App to provide a consistent and integrated environment in which to compile, link and build in a simple way through native. It handles multiple workspace compilation, link and run time creation to provide the most efficient way to manage dependencies between separate workspaces. It detects modifications in source code, and displays and tracks these modifications through the entire build time view, along with other prerequisite workspaces. This provides significant build performance improvement by allowing the user to build only what has been modified. It handles apps code created in multiple development languages: (1) C, C++, and Java for apps development, (2) TIEs in the architecture (fully integrated), (3) IDL Compiler to allow the viewing using Microsoft Visual Basic Access (VBA) or equivalent macro.

Enhance Code Quality through Automatic Check of C++ Coding Rules. The C++ source checker operates at the source stage in the application development cycle for early checking of C++ coding rules to ensure better stability and reduce the number of code defects. Debugging time is reduced drastically and the quality of the code is improved.

5.2.3.2. Open APIs & Interfaciong

3DEXPERIENCE services for changing the public schema model and user data substantiated from the public schema model can be executed using Java or C++. Besides, all 3DEXPERIENCE applications are modular providing APIs distinct for each application, and all functions are recorded using the standard Javadoc convention. The JavaScript API, protocols and widget format allow creating new 3DDashboard widgets. REST Web Services allow connecting to 3DEXPERIENCE platform services using 3DPassport authentication protocol and to access 3DSwym data and 3DSpace People and Organization Data.

The platform enables the federation of product data created via diverse tools throughout the entire lifecycle in a single data-centric referential. For that, it follows every standard in the market, offering a variety of data connection solutions. The platform permits many classes of openness (multifaceted) that can be grouped into three types (see table below).

	FUNCTIONS	Tools	Standards
Traceability	Visualisation of links between objects of different systems, and navigation through those links (from data in ↔ outside the platform) to understand impact of changes, coverage of data by processes and collaboration around this information.	CATIA System Navigation and Traceability (TRA)	n/a
Data Exchange	Based in standard formats, allows exchanging data between systems (e.g. external tools). It implies data duplication in different systems (can lead to data discrepancy).	n/a	ReqIF, FMI, AUTOSAR
Data Federation	Sharing data between systems by synchronization or/and linked data without duplication. Can be supported by real-time collaboration between tools by use of web services.	ENOVIA DesignSync (BLD)	OSLC, Restful

Table 5: Table List of discussed tools and standards

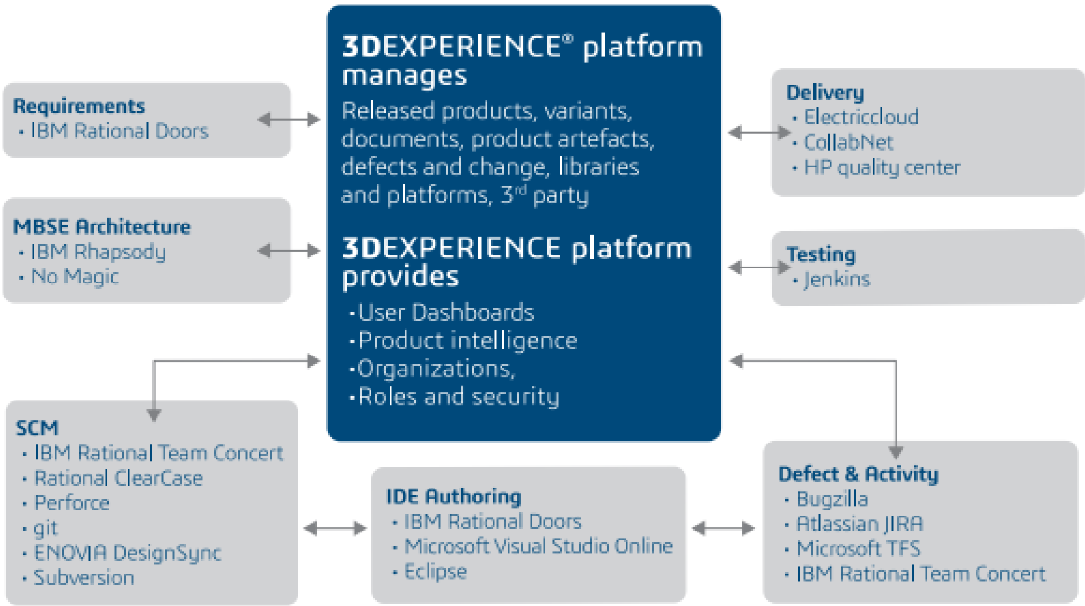

Figure 53: Openness for Application Lifecycle Management (ALM)

For example, in the automotive industry, prominent standards such as ReqIF, AUTOSAR, and FMI that have been adopted at a worldwide level are now fully supported for both export and import by the 3DEXPERIENCE platform. These standards were mainly driven by the needs of automotive industry OEMs and suppliers to address growing complexity of processes dominated by embedded systems software.

REQIF contains an XML data model that permits automated transfer of specifications, including graphics and tables. With ReqIF, an exchange file is exported from a RM tool that can be imported and understood by another system. In addition, it includes clear rules for the description and identification of the data. The 3DEXPERIENCE platform can export and import requirements using ReqIF.

Functional Mock-up Interface (FMI) is a tool independent standard to support both model exchange and co-simulation of dynamic models. Its major goal is to improve the exchange of simulation models between suppliers and OEMs, building a strong foundation for the collaborative development of complex mechatronic systems. FMI is supported by over 100 tools and is used by automotive and nonautomotive organizations throughout Europe, Asia and North America.

AUTOSAR (AUTomotive Open System ARchitecture) is a worldwide development partnership that delivers an open and standardized automotive software architecture. It introduces new software architecture and development methods, including a standardized layer between application software and hardware (ECU). In 2012, AUTOSAR extended its standard into non-automotive areas.

All these standards—ReqIF, FMI, AUTOSAR—are at the core of the 3DEXPERIENCE platform to enable today's and tomorrow's industries to develop and simulate software intensive experiences. Dassault Systèmes will continue to integrate the latest standards to allow industries to master the hardware/software complexity and define, build, manage and experience multidiscipline products. Among those standards, Dassault Systèmes will build OSLC connectors, but also other means for Openness, as presented next.

Knowing the data linked across systems is a fundamental need of systems and software engineering, even before the data exchange. System Navigation and Traceability (TRA) allows to guarantee end-to-end traceability and cooperation on system and software models no matter the system considered. For any tool, be it inside the 3DEXPERIENCE platform or outside of it (DOORS, Rhapsody or Matlab/Simulink…), the traceability link can be navigated and the impact of changes understood. TRA allows the particular option to understand, share, review and collaborate on a holistic system view, even with diverse tools and different organizations. Connectors will gradually be included and users can add new connectors with ease for proprietary tools. Besides, system traceability supports OSLC-RM as a customer and can thus navigate to any OSLC compliant provider tool.

The Open Services for Lifecycle Collaboration (OSLC) is an open community defining specifications for the integration of software engineering tools. The base for OSLC are internet standards like Linked data, RESTful web services or RDF. OSLC is the core for integration between the suite of tools IBM Jazz (DOORS, RTC…). It is based on Internet standards (e.g. HTTP, RDF) using Linked Data Model, and specifies a common tool protocol for creating, retrieving, updating, and deleting (CRUD) lifecycle data. Any tool or other program client can use this protocol to talk to any other tool that implements the specification. Embedding the HTTP URL of one resource in the representation of another allows to achieve the Linking. Domains are defined beyond the essential core definition of OSLC: Requirement Management and Change Management are the most developed domains today. On the other hand, future domains will cover quality management to connect verification data or architecture management for linking architecture components. By using OSLC for domain-specific ALM tools integration with 3DEXPERIENCE, one connector allows you to connect to every tool compliant, that can provide or receive the shared data. In the fast-shifting ALM environment, the common thing is to wait for new tools to offer the right connector.

5.2.3.3. Scope

Software development usually happens in an isolated environment, with separate tools administrated by different teams. When integration between teams happens, it is generally through a disconnected process. ENOVIA DesignSync brings software development environment and content metadata into the 3DEXPERIENCE platform. Thus, Software Code Management (SCM) is integrated into the product lifecycle management (PLM) tool chain and platform, which is not trivial. Most factories have lots of software IP code managed and their development teams invest much in training and tooling for these pre-existing systems. Migrating source code to a new system is a difficult and time-consuming exercise, and retraining developers is costly and time-consuming. However, through the ENOVIA DesignSync solution, software development organizations can take advantage of Software Lifecycle Management (SWLM) benefits without the major investment associated.

The 3DEXPERIENCE platform enables the SWLM while managing source code in different legacy repositories; developers keep working in their present development environments and current code management tools. A fully controlled lifecycle and faster development is obtained by the product team and management while avoiding to disturb the development teams and unnecessary additional cost of migration, retraining and retooling.

The federation of tools and the data management are eased by standard connectors and exchange formats; however, its customisation to each process is usually a requirement in real life. Therefore, the actual workflow of data collaboration has often to be modelled and implemented with direct integrations between tools; which requires a high level and light weight framework for integration based on web services. Indeed, RESTful are a fundamental part of the 3DEXPERIENCE architecture, with an adapted, lightweight interface supported by modern programming languages and frameworks. When novel applications are improved and created, new REST services APIs are developed, bringing key interfaces and openness enabling the adaptable functioning without source code modification. 3DEXPERIENCE provides the correct authentication, licensing and access control with RESTful services developed on top. The services provide full control of the underlying resources to read and write, and guarantees data integrity and completeness.

5.3. CyberFactory Processes

5.3.1. Factory Internal Logistic Planning & Simulation

For logistical processes inside a factory, the placement of facilities and the resulting material flow are key factors. In that context, facilities are all elements, which are involved in the value-added process. Examples for facilities are machines, storage locations, logistics like cranes or tracks and more. An optimal arrangement of these resources in the form of a factory layout results in the lowest possible material handling costs (MHC). According to Emami[360], these account for between 20-50 percent of a company's total operational production costs. Tompkins and White[361] stated that an efficient factory layout reduces operating costs by 10-30 percent. In direct contrast, a poor layout increases production costs up to 36 percent.[362] This demonstrates the link between layout planning and business productivity.

To determine the best arrangement of elements, layout planning is used. According to Wirth et al.[363] the following hierarchical stages are distinguished:

- General development planning
- Rough layout planning
- Detailed layout planning

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[360] Emami, S., & Nookabadi, A. S. (2013). Managing a new multi-objective model for the dynamic facility layout problem. The International Journal of Advanced Manufacturing Technology, 68(9-12), 2215-2228.
[361] Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). *Facilities planning*. John Wiley & Sons.
[362] Balakrishnan, J., & Cheng, C. H. (2007). Multi-period planning and uncertainty issues in cellular manufacturing: A review and future directions. *European journal of operational research*, *177*(1), 281-309.
[363] S. Wirth, H. Mann und R. Otto, Layoutplanung betrieblicher Funktionseinheiten: Leitfaden. Techn. Univ. Chemnitz, Inst. f. Betriebswiss. u. Fabriksysteme, 2000.

The general development planning phase handles the positioning of structural elements such as office buildings, storage areas, parking lots and productions halls. The purpose on this stage is the optimization of the material flow between buildings. The rough layout planning deals with the positioning of production and storage areas within a production hall. Further details are determined in the detailed layout planning. In this phase the design and positioning of production facilities, workstations and logistics systems is determined.[364]

In an efficient layout, all machines, logistics, storage locations and other elements are arranged as resistance-free as possible. Due to the high amount of possible arrangements and boundary conditions, there are many layout configurations. To determine the most optimal layout, simulations are carried out with computers. However the required computing time increases exponentially with the problem size. Such problems are called NP-complete problems.[365] The difficulty in determining the optimal arrangement of elements inside a factory is known as the *Facility Layout Problem* (FLP).

5.3.1.1. Facility Layout Problem

FLP related studies deal with the optimal arrangement of system components within the factory floor, considering various boundary conditions. The boundary conditions depend to the optimization criterion and therefore vary greatly. They include e.g. the size of the available area, its shape, predetermined zones for receiving or delivering goods and different possible material flows. In this work and scope of the project, the FLP is considered with a focus of logistical processes inside a factory.

Transport flows inside the factory

Figure 54 shows seven different possible material flows inside a factory, which lead to a different classification of the FLP.

[364] L. S. Bochmann, „Entwicklung und Bewertung eines flexiblen und dezentral gesteuerten Fertigungssystems für variantenreiche Produkte,“ Diss., ETH Zurich, 2018.
[365] Vitayasak, S., Pongcharoen, P., & Hicks, C. (2017). A tool for solving stochastic dynamic facility layout problems with stochastic demand using either a genetic algorithm or modified backtracking search algorithm. International Journal of Production Economics, 190, 146-157.

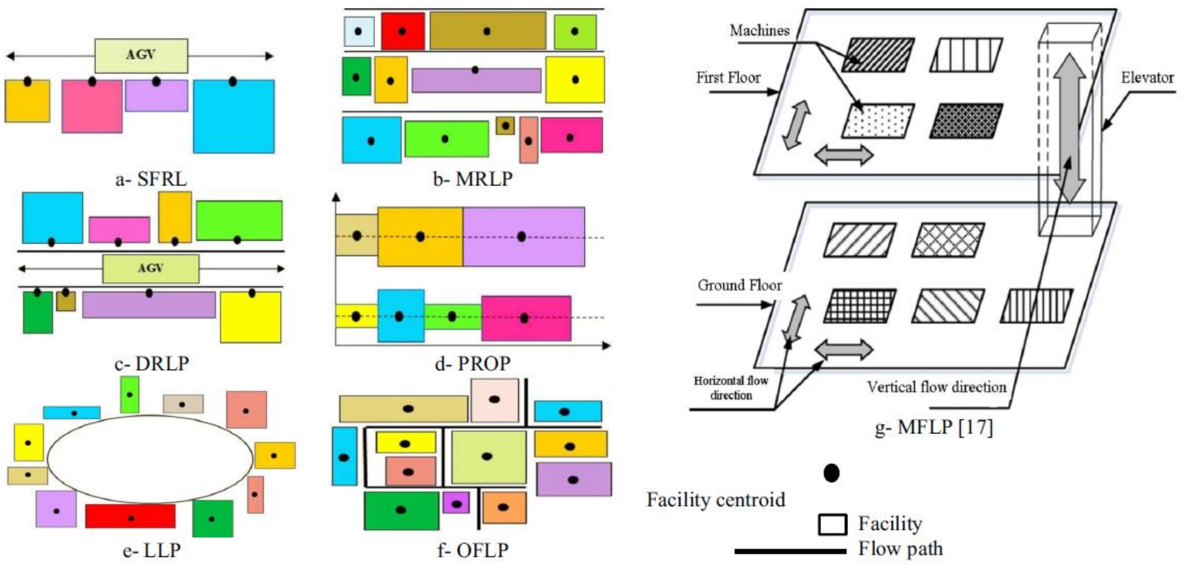

Figure 54: Considering the material flow inside a factory366

a) The *single-row layout problem* (SRLP) is dealing with the optimal placement of rectangular facilities along a line in order to minimize total arrangement costs. These are determined as the sum of the product flows from center point to center point (Facility Centroid).

b) The *multi-row layout problem* (MRLP) adds a number of rows into the two-dimensional space. The goal is to find the best suitable row for a facility.

c) The *double-row layout problem* (DRLP) involves the optimal placement of rectangular facilities with varying width that are placed on opposite sides of the floor. The goal is to minimize the handling costs of an AGV-system.

d) The *parallel-row ordering problem* (PROP) arranges facilities with common characteristic along one row and the remaining facilities on a parallel row. PROP assumes that the arrangements in parallel rows start from a common point and that no space is allowed between two neighbored facilities. DRLP assumes that the distance between two parallel rows is zero, while PROP does not.[367]

e) The *loop layout problem* (LLP) concerns about finding the optimal location of n-facilities in a closed ring network in order to reduce the MHC.[368]

f) The *open-field layout problem* (OFLP) applies to situations where no predefined material flow as proposed in a-e is available.

[366] H. Hosseini-Nasab, S. Fereidouni, S. M. T. F. Ghomi und M. B. Fakhrzad, „Classification of facility layout problems: a review study,“ The International Journal of Advanced Manufacturing Technology, Jg. 94, Nr. 1-4, S. 957–977, 2018.

[367] Amaral, A. R. (2013). A parallel ordering problem in facilities layout. Computers & Operations Research, 40(12), 2930-2939.

[368] Hungerlaender, P. (2014). Single-row equidistant facility layout as a special case of single-row facility layout. *International Journal of Production Research*, *52*(5), 1257-1268.

g) For multi-storey buildings, vertical transport flows must also be taken into consideration, according to Kochhar and Heragu[369], such situations are defined *multi-floor layout problems* (MFLP).

Regarding the actual flow movement two types are distinguished, the backtracking and bypassing. Both influence the product flow, see Figure 55.

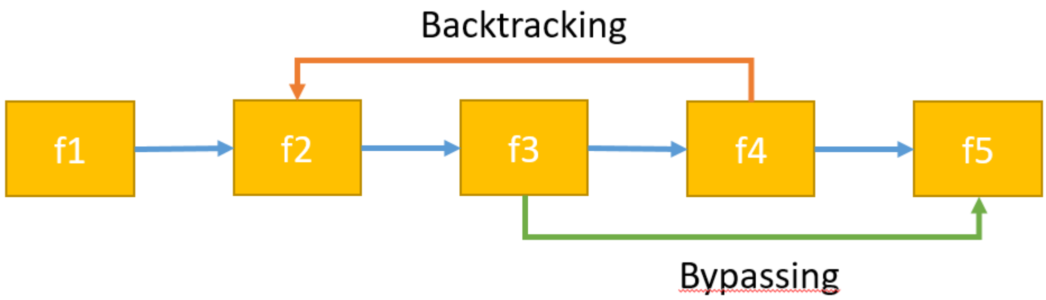

Figure 55: Backtracking and bypassing (own representation based on Drira et al.370)

In this example a production line of five stages is shown. The boxes are arbitrary facilities (machines, robots etc.) and the blue arrows indicate the product flow. In an efficient layout the products pass through the production stages one after the other. However most factories produces different products and not every product needs to follow this procedure. Bypassing is happening in the actual flow direction, however one facility is being skipped. Backtracking occurs when a part skips a facility in the opposite flow direction. Zhou[371] referred to these scenarios as *production line formation problems* (PLFP).

5.3.1.2. Modelling the Facility Layout Problem

Depending on the constraints, different mathematical models are used to solve the FLP. In a recent survey Hosseini et al.[372] distinguish seven different modelling classes. Most often, the FLP is modelled as *quadratic assignment problem* (QAP) or in form of the *mixed integer programming* (MIP). In QAP modelling, the layout is divided into n equal-sized rectangular locations, see Figure 56.

In discrete representation, each facility is assigned to one location and vice versa.[373] Larger facilities are assigned to several locations. In Figure 56 the factory floor is divided into 16 equally sized rectangles which are occupied by eight facilities. They facilities 2, 3, 4 and 7 occupy exactly one location, the others occupy depending to their size several. The QAP

[369] Kochhar, J. S. (1998). MULTI-HOPE: a tool for multiple floor layout problems. International Journal of Production Research, 36(12), 3421-3435.
[370] Drira, A., Pierreval, H., & Hajri-Gabouj, S. (2007). Facility layout problems: A survey. *Annual reviews in control*, *31*(2), 255-267.
[371] Zhou, J. (1998). Algorithmes et outils pour l'analyse des flux de production a l'aide du concept d'ordre (Doctoral dissertation, Université Louis Pasteur (Strasbourg)).
[372] H. Hosseini-Nasab, S. Fereidouni, S. M. T. F. Ghomi und M. B. Fakhrzad, „Classification of facility layout problems: a review study," The International Journal of Advanced Manufacturing Technology, Jg. 94, Nr. 1-4, S. 957–977, 2018.
[373] Konak, A., Kulturel-Konak, S., Norman, B. A., & Smith, A. E. (2006). A new mixed integer programming formulation for facility layout design using flexible bays. Operations Research Letters, 34(6), 660-672.

formulation for determining the relative location of facilities in order to minimize MHC according to Balakrishnan et al.[374] is:

$$\min \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} \sum_{l=1}^{N} f_{ik} d_{jl} X_{ij} X_{kl} \quad (1)$$

s. t.

$$\sum_{i=1}^{N} X_{ij} = 1, j = 1, \dots, N \quad (2)$$

$$\sum_{j=1}^{N} X_{ij} = 1, i = 1, \dots, N \quad (3)$$

- N Number of facilities in the layout,
- F_{ik} Flow cost from facility i to k,
- djl The distance from location j to l,
- i, k Departments in the layout
- j, l Locations in the layout
- Xij The 0, 1 variable for locating facility i at location j.

The objective function (1) represents the sum of the flow costs over every pair of facilities. The second equation (2) ensures that each location contains only one facility and equation (3) guarantees that each facility is placed in only one location.

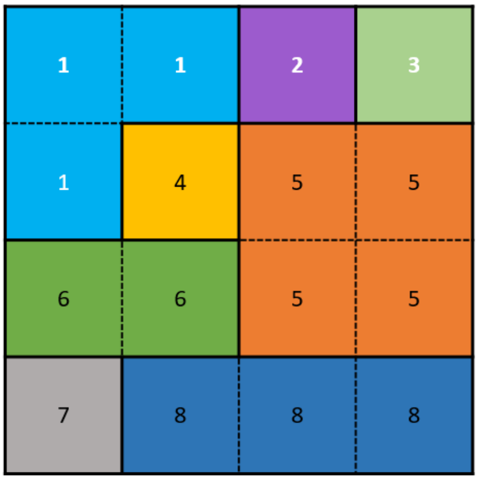

Figure 56: Discrete representation of the factory layout (own representation based on Drira et al.375)

To find the most optimal solution of the FLP meta-heuristic algorithms are used. As mentioned before all kind of the FLP are NP-complete, meaning that the computing time

[374] Balakrishnan, J., Cheng, C. H., & Wong, K. F. (2003). FACOPT: A user friendly Facility layout Optimization system. Computers & Operations Research, 30(11), 1625-1641.
[375] Drira, A., Pierreval, H., & Hajri-Gabouj, S. (2007). Facility layout problems: A survey. *Annual reviews in control*, *31*(2), 255-267.

required to solve a problem increases exponentially with the problem size[376]. This is the main reason why exact algorithms are only applicable for very small sized layouts, which are lacking an industrial usage. Meta-heuristic algorithms can be utilized to simulate possible locations of the factorial layout and their impact to the MHC in a reasonable time. Examples for these kind of algorithms are genetic algorithms, simulated annealing, tabu search algorithm and more. The following section gives an overview with focus of simulation approaches to solve the FLP.

5.3.1.3. Simulation approaches with focus on layout planning

Centobelli et al.[377] proposed a layout reconfiguration and technological solution for the parts feeding system of an industrial plant. They consider layout planning to be one of the most important aspects of the Digital Factory since it is capable of providing huge support in the decision-making process. Their analysis aimed at reducing the production lead times by using simulation. The simulation results showed a potential material handling time reduction in the range of 1.6 % to 8.6 %.

Naranje et al.[378] proposed a discrete simulation model for the efficient management of inventory and improvement of the productivity. They conducted a research project at Eagle Industries. They validated the solution by using a Tecnomatix[379] simulation. In the optimized inventory layout the fastest moving items are placed in close proximity with lifts or unloading area or even closest to the production area. Dead stocks are placed in the farthest available space in the warehouse. By that, they achieve a stress and time reduction for the worker. Apart from that, they investigated and analysed the shop floor and detected various time consuming process. The proposed layout changes were validated via simulation.

Liang and Fang[380] have presented an approach to calculate highly complex systems concurrently using decentralized GA. To do this, they divided the layout into different subsystems, which are calculated in parallel by an identical GA. After each iteration, data is exchanged between adjacent subsystems. In six experiments, the results of a conventional GA are compared with the parallelized GA. In all cases the parallelized GA approaches the convergence value faster. With increasing complexity, this advantage becomes more obvious, although the results show a higher volatility than the simple GA.

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376 Vitayasak, S., Pongcharoen, P., & Hicks, C. (2017). A tool for solving stochastic dynamic facility layout problems with stochastic demand using either a genetic algorithm or modified backtracking search algorithm. International Journal of Production Economics, 190, 146-157.
377 Centobelli, P., Cerchione, R., Murino, T., & Gallo, M. (2016). Layout and material flow optimization in digital factory. International journal of simulation modelling, 15(2), 223-235.
378 Naranje, V., Reddy, P. V., & Sharma, B. K. (2019, April). Optimization of Factory Layout Design Using Simulation Tool. In 2019 IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA) (pp. 193-197). IEEE.
379 A Siemens AG software: https://www.plm.automation.siemens.com/global/en/products/tecnomatix/
380 Liang, W., & Fang, D. (2019, December). Decentralized Genetic Algorithm for Dynamic Plant Layout Problem. In IOP Conference Series: Materials Science and Engineering (Vol. 677, No. 5, p. 052080). IOP Publishing.

Ding et al.[381] proposed an implementation of a virtual factory layout in a 3D virtual environment. They aim to deliver the possibility to experience the actual setting of a factory design and simulation, to minimize interpreting errors of 2D layouts. The developed implementation of the virtual plant layout and simulating system is based on OSG with Microsoft Visual C++. The physical 3D-models are created with 3DS MAX (Autodesk).

Bobby and Jenson[382] used the software ARENA (Rockwell Automation) to simulate an existing factory layout of the company Kerala Electrical and Allied Engineering. Their main aim is to find out the most efficient arrangement of machines in the shop floor. Their simulation visualizes the individual movements from one machine to other. For ARENA they calculated the machining times of each machine and arrival times of materials. This way they detected by simulation the machines with the largest queues and their efficiencies. Based on this analysis they argued that a change in the layout could improve the utilization of the machines and that an advanced material handling system is required.

Nafors et al.[383] looked at the gaming sector and use virtual reality and 3D-imaging in an industrial context by using a hybrid digital twin. In three separate industrial cases, they studied the usage for factory planning scenarios and identified improvement potential.

Mladineo et al.[384] created a cyber-physical representation of a factory, which contains data about machines, workplaces, transportation routes and transport intensities. They aim to improve the factory layout by minimizing the transport efficiency (transport intensity multiplied by distance). They use the software visTable[385] for the virtual representation of a real factory layout. In future work they see further research gap on how to integrate genetic algorithms.

Dias et al.[386] demonstrated a concept on how to take advantage of simulation in order to optimize factory layouts and processes. They used AutoCAD for the layout design, WITNESS (SIMPLAN) for simulation and Microsoft Access as a database. Their approach is based on previous work of Vik et al[387] [388], who managed to integrate these software

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[381] Ding, J. H., Wang, Y. G., & Chen, K. (2010). An interactive layout and simulation system of virtual factory. In Applied Mechanics and Materials (Vol. 20, pp. 421-426). Trans Tech Publications Ltd.
[382] John, B., & Jenson, J. E. (2013). Analysis and simulation of factory layout using ARENA. International Journal of Scientific and Research Publications, 3(2), 1-8.
[383] Nåfors, D., Berglund, J., Gong, L., Johansson, B., Sandberg, T., & Birberg, J. (2020). Application of a Hybrid Digital Twin Concept for Factory Layout Planning.
[384] Mladineo, M., Banduka, N., & Peko, I. (2017). Factory Layout optimization through Cyber-Physical System and Virtual Reality. Advancing in Human-Computer Interaction, Creative Technologies and Innovative Content, 1-30.
[385] https://www.vistable.de/
[386] Dias, L. M., Pereira, G. A., Vik, P., & Oliveira, J. A. (2014). Layout and process optimisation: using computer-aided design (CAD) and simulation through an integrated systems design tool. International Journal of Simulation and Process Modelling, 9 (1-2), 46-62.
[387] Vik, P., Dias, L., Pereira, G., Oliveira, J., & Abreu, R. (2010). Using SIMIO in the design of integrated automated solutions for cement plants. In Workshop on Applied Modelling and Simulation.
[388] Vik, P., Dias, L., Pereira, G., & Oliveira, J. (2010). Improving production and internal logistics systems–an integrated approach using CAD and simulation. In ILS2010-3rd International Conference on Information Systems, Logistics and Supply Chain-Creating value through green supply chains. Casablanca (Morocco), April (pp. 14-16).

resources in production systems (a tool called IDS). The system was applied onto an internal logistic issue of an automotive supplier. They claim to have doubled the previous throughput within 1.5 weeks, while traditional approaches would have required four weeks for this job.

Prajapat et al.[389] uses the Discrete Event Simulation (DES) for the analysis and factory layout optimization of a repair facility. The DES model was created in WITNESS with a link to an Excel spreadsheet for gathering Key Performance Indicator (KPIs). They validated their model in four different scenarios and run it for 25 simulated weeks. With their second scenario, they observed an improved match.

5.3.2. Zero Defect Manufacturing Process Planning & Simulation

Manufacturing has always sought a high-quality performance pursuing "near zero" perfection, aiming at quality improvements both of products and manufacturing processes. Approaches such as TQM, (digital) lean manufacturing and zero defect have been flanked by statistical tools capable of analysing data from the field to generate indicators to support the decision-making activities according to the logics of quality management.

Zero-Defect Manufacturing is a paradigm that aspires to develop methodologies, technologies and integrated tools for maintenance, quality control, and logistics of production that takes advantage of the knowledge of the process and the system. The most relevant aspects are

(1) predictive models of degradation machine states;

(2) condition-based maintenance approaches able to prevent deviations without interfering with the performances of the logistics system;

(3) models and methods for predicting the defects impact on subsequent production phases in order to identify proactive solutions (rework and repair online).

Therefore, it aims to reduce defects as much as possible thanks to the implementation of preventive actions. Some of these actions include worker motivation in order to increase their consciousness and encourage them to do the job right the first time.

5.3.2.1. ZDM in the era of digitalization

Industry 4.0 is characterised by the automation and data exchange in manufacturing technologies. It connects and integrate digital environments throughout the value chain focusing on the end-to-end digitization of everything everywhere. Industry 4.0 networks new technologies, platforms and data spaces to create value by generating, analysing and communicating data seamlessly.

In that light, for companies to achieve zero-defect production, operations and products must be smart and connected. The digitalization of manufacturing systems allows access

[389] Prajapat, N., Waller, T., Young, J., & Tiwari, A. (2016). Layout optimization of a repair facility using discrete event simulation. Procedia CIRP, 56, 574-579.

to data by implementation of CPPS (Cyber Physical Production Systems) and generates connectivity and interoperability through the IIoT (Industrial Internet of Things).

To this end, the interaction between hardware/software and data management makes the ZDM concept easier to be implemented due to the availability of the required amount of data for advanced technologies such as machine learning to work properly. Although a lot of effort is still need for better integration and coordination of the capabilities of each enabling technology, ZDM is expected to become the new standard for companies towards more efficient and eco-friendly production lines with zero defects.

Defects arise when a process or a product does not perform within its specification, resulting in a non-compliant condition. Defects cause failures and result in loss of resources and increased costs. Zero defect in Industry 4.0 requires obtaining anticipated information on the quality of the parts during the respective process steps and evaluating the influence of deviating process parameters.

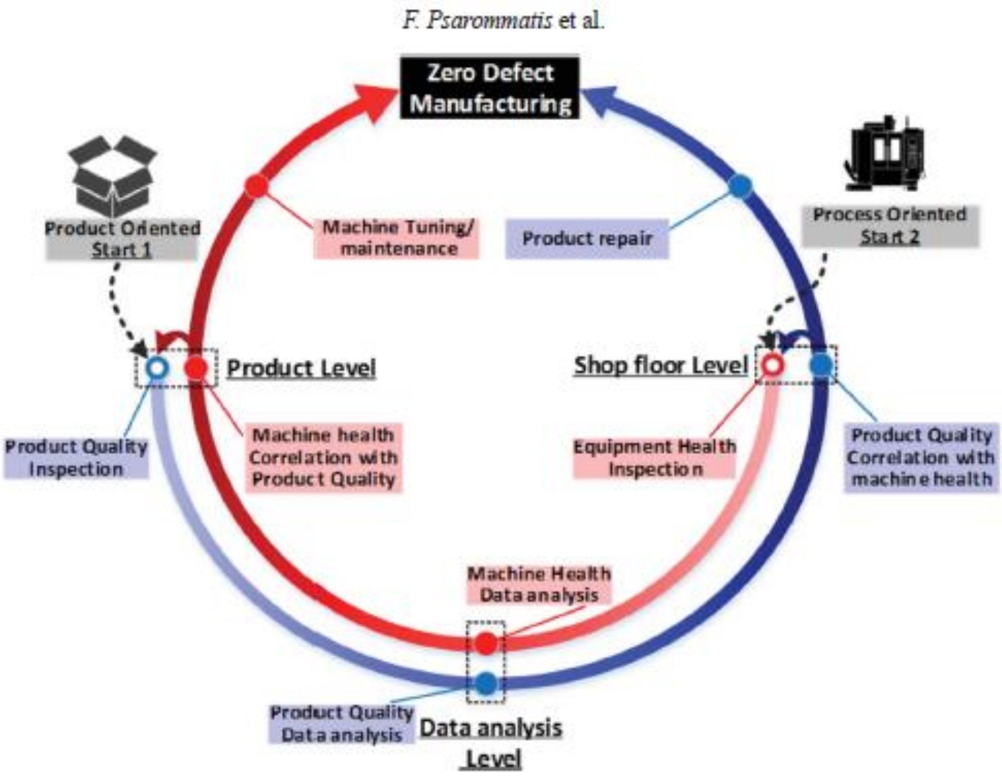

Figure 57: Zero Defect manufacturing concept390

Many of the current methods and tools in the frame of quality control and management are not directly Industry 4.0 compatible:

- Rely on fixed models of the processes, often tied to fixed devices;
- On premise focused, relying on a restricted set of smart capacity from the field

[390] F. Psarommatis, G. May, P. Dreyfus and D. Kiritsis, “Zero defect manufacturing: state-of-the-art review, shortcomings and future directions in research,” *International Journal of Production Reserach,* p. 20, 2019.

- Linear, fixed models of assets and processes;
- High-touch integration to automation;
- Rely on factory-context workflow.

5.3.2.2. Smart Manufacturing and Industry 4.0

Changes are needed to be more directly compatible with Industry4.0. According to Deloitte insights[391], there are five key characteristics of a smart factory:

1) Connected: assets of a smart factory, such as processes and materials, should be connected so that both traditional data sets and new sensor data can be updated constantly. It enables real-time decision support, supplier and customer collaboration, and inter-department collaboration in the factory.
2) Optimized: a smart factory should have optimized performance in terms of high yield, uptime and quality, with low cost and waste rate, enabled through automated workflows, synchronized assets, improved tracking and scheduling, and optimized energy consumption.
3) Transparent: the real-time data should be transformed actionable insights for both humans and autonomous decision-making systems supported by real-time data visualization solutions.
4) Proactive: based on historical and real-time data, a smart factory should have the ability to predict future outcomes enabling systems and humans to anticipate and act before quality or safety issues arise.
5) Agile: advanced smart factories should allow self-configuration of the equipment and material flows to adapt to schedule and product changes with minimum intervention.

All those key issues play a vital role in understanding the Zero-Defect Production Concept and more important take action towards it. Smart factories are more responsive, proactive, and predictive, thus avoiding operational issues and other productivity challenges.

In that light, smart factories are empowered to be able to adjust to and learn from data in real time through:

- Connectivity/Sensing/Mobile
- Cloud/Advanced analysis
- Decentralization
- Vertical and Horizontal integration
- Interoperability

[391] https://www2.deloitte.com/insights/us/en/focus/industry-4-0/smart-factory-connected-manufacturing.html

Thus, AQ practices and tools require incorporating existing classical quality control and management solutions, but also offering additional features and functionalities. AQ solutions allow capabilities like:

- Acceleration of IT operations
- Achieve accurate information on processes and product quality throughout each process step based on real-time data
- Continuous improvement capabilities due to integrated advanced analytics frameworks
- Greater visibility into process quality levels and greater accuracy in predicting performance over time both at plant level and at supply chain level
- Increase of efficiency, revenue, accuracy and yield of production
- Interoperability of IT infrastructure with other manufacturing and operational systems (ERP, MES, company own, etc.)
- Measuring compliance empowerment and traceability to the machine level
- Plant performance transparency and understanding across multiple metrics
- Quantify daily production impact in financial performance with visibility to the machine level
- Unite quality management and compliance systems.

The reason is that many of the classical IT solutions are standard systems and not agile enough to match specific company quality needs in an autonomous way. Smart software solutions can automate quality processes. This means that companies can adapt smart solutions to their specific needs, considering all their quality aspects lowering humans' intervention in the quality processes.

Smart solution can be connected with the overall ICT landscapes and production environment and is processing information in real-time. Operators are empowered with automatic assistance, enabling them to execute product qualification procedures, ensuring that all qualification requirements are within the predefined range.

In order to achieve the automated quality goals for a system of systems, some key issues that constitute the framework necessary to achieve Zero-Defect Production processes are presented below.

- Measurement Equipment. The lack of interoperability between IT systems and measurement equipment prevents the availability of real-time data, often linked to the machine or factory system. Otherwise, equipment connected to each other ensures comprehensive monitoring and provides up-to-date information thanks to interoperable functionalities that enable automatic real-time measurements. This allows smart systems not only to read data, but also to close the information loop in feedback, recalibrating the activities intelligently.
- Quality Reporting. To achieve perfect quality levels, smart and automatic reporting procedures must be in place. Smart means based on real-time data, generated instantaneously and correlating relevant information. Classical quality systems are

not deep enough embedded into IT landscapes. This lack of automation limits the quality reporting and therefore efficiency. Smart quality reporting requires a new type of software with all-embracing interconnectivity. Smart software solutions automatically record quality data and provide any kind of configured / customized, quality reports. Interoperability capabilities, with multiple system, machine, station or process, enable to get instantly updated reports accessible from smart devices. Smart quality reporting predefines relevant information and provides the right conclusions, in an intuitive and simple manner, relieving operators from manual work.

5.3.2.3. Standards for Industry 4.0 ZDM

IT standards for Industry 4.0 and the manufacturing disciplines covered within digitalisation has not been satisfactory developed yet. However, the development of the RAMI, Reference Architectures RAMI for Industry 4.0 covers both the framework and platform issues that can support ZDM.

- The “Life Cycle & Value Stream:” axis: The left horizontal axis represents the life cycle of facilities and products, based on IEC 62890 for life-cycle management.
- The “Hierarchy Levels” axis: Indicated on the right horizontal axis are hierarchy levels from IEC 62264, the international standards series for enterprise IT and control systems.
- The “Layers” axis: The six layers on the vertical axis serve to describe the decomposition of a machine into its properties structured layer by layer, i.e. the virtual mapping of a machine. Such representations originate from information and communication technology, where properties of complex systems are commonly broken down into layers.
- The “Hierarchy Levels” (with IEC62264) dimension is based on the classic ISA-95 which dates back to the 1990s (but is still maintained). The interface between control functions and other enterprise function based upon the Purdue Reference model for CIP as published by ISA

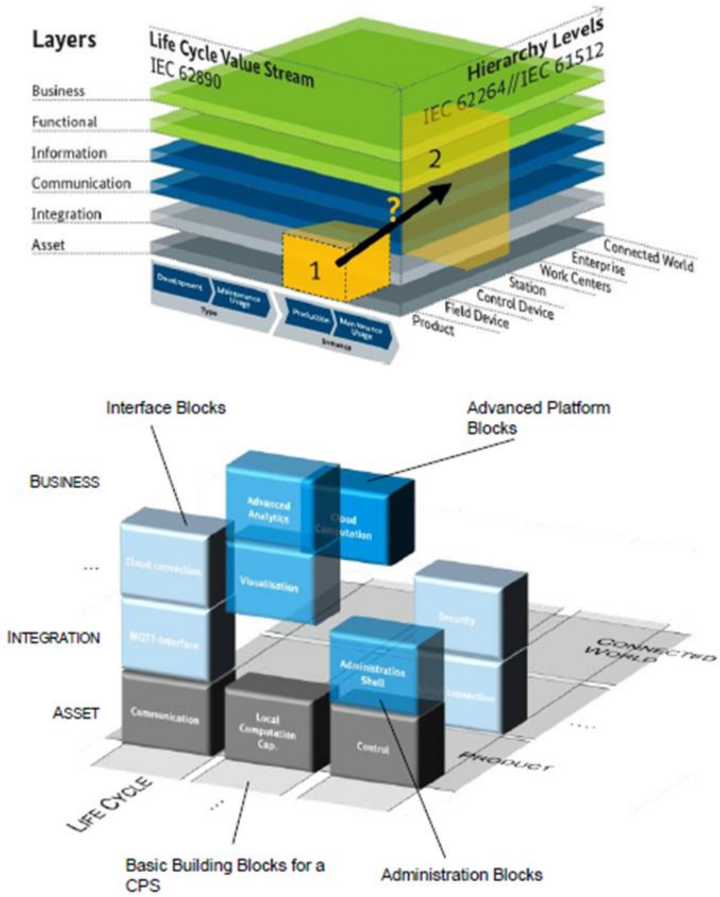

Figure 58: Architectures RAMI for Industry 4.0[392]

Within manufacturing standards there are quite a few that consider how existing standards can be modified an improved to meet the challenges of Industry 4.0 implementation. Interesting international and European standardization organizations are the International Electrotechnical Committee (IEC), the International Organization for Standardization (ISO), the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC), in particular the technical committee ISO/TC 184 “Automation systems and integration”, ISO/TC 108/SC 5 “Condition monitoring and diagnostics of machine systems”, IEC/TC 65 “Industrial-process measurement, control and automation” and the CLC/TC 65X “Industrial-process measurement, control and automation”. In addition, we have ISO 22400 which proposes a list of 34 KPIs for manufacturing operations management involving four information categories: production operations management, maintenance operations management, quality operations management, and inventory operations management (Appendix II).

- **Data Analytics.** Smart software statistical quality analyses are created by automatically monitoring production environments. Using real-time data empowers the creation of varieties of statistical quality analyses, which fulfil AQ needs and tailored requirements.
- **Data Security software vs hardware in Industrial IoT.** In typical industrial IIoT area it will always raise a question of security, this is often the software versus

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[392]https://www.zvei.org/en/subjects/industrie-4-0/the-reference-architectural-model-rami-40-and-the-industrie-40-component/

hardware. Software-based security solutions encrypt the data to protect it from theft. However, a malicious program or a hacker could corrupt the data in order to make it unrecoverable, making the system unusable and unstable, in an industrial environment this can hamper the production.

Hardware-based security solutions can prevent read and write access to data and hence offer very strong protection against tampering and unauthorized access, which can lead to slow asses for the operators and bad internal communication. It is also a security where hacker could thru software solutions i.e. take control over the machinery which can lead to a total brake shut down on a plant.

5.3.2.4. Opportunities and challenges

ZDM relies on Industry 4.0 technology and devices, autonomously communicating with each other along value chains. The integration of process and parts monitoring and control along the value chain can enhance traceability and earlier detection enabling quality improvements and defect reductions.

Quality management in digitized systems does not only mean avoiding defective products delivered to the customer but acting in advance along the value chain to guarantee quality performance by making all the processes of an organization efficient[393].

Typically, there are two ways to improve the products' quality: optimal process design for quality improvement and statistical process control. Now in the industrial big data era, a lot of data is available, including sensor readings, inspection measurements, optical images as well as structured/unstructured data sources. This multi-source data is becoming an indispensable resource for production managements and quality improvement. Complexity of the quality control rises also since there is need to go beyond one manufacturing process quality control. In a value chain there may be multiple manufacturing and assembly stations each contributing to the product quality.

The measurement data contains a large amount of manufacturing process and product information. Technological means to control quality of the manufacturing process include also perception of the environment (i.e. tracking operator movements), feedback from the operators or machines, and external information collected from web, customers, product use phase and supply chains.

At the same time, the modelling technology of multi-station manufacturing system is being improved continuously. Together with the different data sources available, the manufacturing process modelling techniques provide great potential for root cause identification of manufacturing process failures. However, it requires that new data analysis methods are applied such as methods based on the combination of principal component analysis (PCA) and pattern recognition.

Therefore, Industry 4.0 offers opportunities in quality management: reduction in complexities, costs, risks, waste, dependency, vagueness and increase simplicity, convenience, interconnectivity, flexibility, productivity human-machine collaboration.

[393] P. Schlegel, K. Briele and R. H. Schmitt, "Autonomous Data-Driven Quality Control in Self-learning Production Systems," *Advances in Production Reserach,* pp. 679-689, 2019.

Nevertheless, it also challenges to overcome technological complexity, the need for new skills as well as the adoption of new technologies.

The development of high-efficiency production systems allows to minimize production costs, improve the productivity and quality of the product and the manufacturing process. High production efficiency is in fact a necessary condition for the competitiveness of all companies.

Opportunities	Challenges
Higher Quality, less defects	Quality control systems
Improved timing and scheduling	ERP communication
In-line measurement	Data analysis
Data analytics, Visual analytics, Artificial intelligence	Access to data, data quality, heterogeneous data sources, data storage infrastructures
Virtual product design	
Better operator support (AR/VT)	

Table 6: Efficiency/productivity opportunities vs. challenges

It has become that much more important for manufacturing companies to clearly understand the competitive capabilities they need to develop to attain superior performance.

Opportunities	Challenges
Flexibility/customizing	Logistics and stock control
New business models for the products	Implementation
Improved vendor control	Open systems

Table 7: Competitiveness opportunities vs. challenges

5.3.2.5. Approach to simulation

A manufacturing system is a SoS since it includes different systems (i.e. quality, production, planning & control, and maintenance systems) and the interdependencies within the subsystems generate limitations for the SoS, having an effect on the running of the entire system.

For a SoS approach, fist all the elements of uncertainty and complexity are detected. Second, the objectives and strategies are set. Finally, the architecture and component systems are designed, taking technical, human and economic factors into consideration. Integration with non-production departments, such as engineering, planning and after-sales service, enables new business insights to drive simulation-based production and work-cell self-reconfiguration and multi-stage manufacturing process optimisation avoiding error propagation.

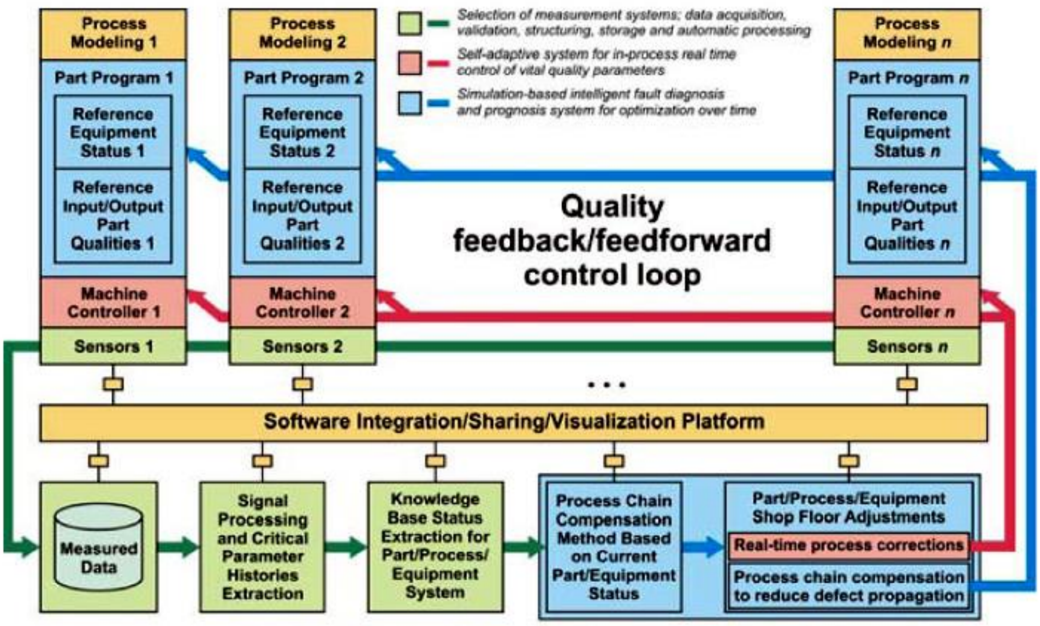

Figure 59: Quality feedback/feedforward control loops

In order to enhance quality and minimise the differences in quality characteristics in multi-level manufacturing processes, the modelling and quality feedback loops at various stages are taken into account. The goal of this feedback is to control system self-adaptation in ever-changing environments and clients' requirements. This allows ZDM self-adaptation as pre-existing controllers change their behaviour after the juxtaposition of quality targets with values gauged. Apart from self-adapting, Cyberfactory tries to analyse and develop self-optimisation methodologies to adapt autonomously and in real-time the quality to reach general optimised results in complex processes. This feedforward process enables to improve quality by reducing deviations in the final product. The major impact of the modelling and simulation of the SoS with feedback/forward loops is to intrinsically reduce the deviations in quality of clients' requirements and product characteristics, increasing process capacities in dynamic environments.

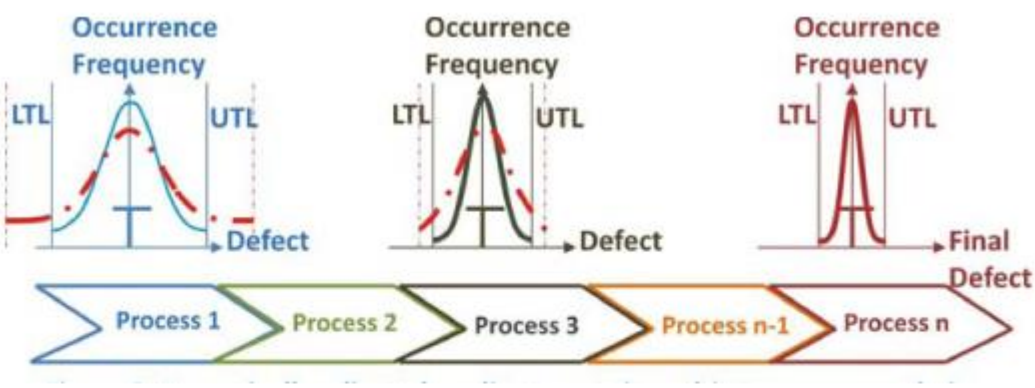

Figure 60: Dynamically adjusted quality targets in multi-stage process chains

The Cyberfactory ZDM strategy will use data to drive efficiencies and improve capabilities in three ways. Connecting workforce, manufacturing assets, facilities and devices to the Internet (IIoT) will enable use cases such as large-scale and small-scale high precision manufacturing, plug & control solutions and smart in-process adaptation. The virtualization and simulation domain will offer advanced digital services based on technologies such as advanced High-Performance Computing (HPC), Digital Twin, Big Data and Machine Learning/Artificial Intelligence (ML/AI). Digital Models will be managed and synchronised with the real-world, and may be used as the basis for automated configuration, simulation and field abstraction.

In computational aspect, the modelling and simulation theory lies upon the formalism of Discrete Event Systems (DEVS). It is implemented in various object-oriented environments. The complexity of behaviour, that modern large systems can exhibit, demands computing power far exceeding that of usual workstation technology. The utilized basic modelling formalism is that of DEVS for representing both continuous and discrete processes, because DEVS representations have significant performance and conceptual advantages. The process of simulation-based decision making is a layered system of functions, including simulation, modelling, optimization and decision making.

In this paradigm, decision makers draw their inferences on experiments with alternative strategies (e.g. reducing the risk, minimizing the time of task execution, etc.), where the best ones, according to some criteria, are put into practice. For realistic models such experiments can't be worked out analytically, therefore they require direct simulation. The technical barriers, addressed in the design of simulation environment, are heterogeneity and portability. For highly precision simulation of large complex systems a multi-layered hierarchical environment is used. The structure of such simulation environment consists usually in three mayor layers: modelling, simulation and searching layer (usually consisting of optimization procedures).

The used simulation systems are executing concurrently different processes in their own heterogeneous and distributed computing agent environment. All advantages of the multiagent systems are also available. The optimisation task at each process is executed by an independent optimization agent, realizing separate algorithm. Each agent has access to its own individual simulator for performing a model-based experiment. Although each simulator is represented as a separate stand-by element, it could be allocated between processors of a multiprocessor distributed computational system. Most generally, an experiment is consisting of numerous simulation trials, aiming at determining how well the particular intelligent controlling (monitoring, managing) agent operates in a prescribed problem environment.

Cyberfactory strategy for ZDM gives estimation for the future states involving the whole production line. The system predicts then with high confidence the expected quality as well as customer satisfaction. The simulation is able to insert desired values and to predict the outcomes, making the zero-defect management system a 'tailor-made' instrument. This strategy tunes the system based on historical, current and future (predicted) data to fine-tune the system to preserve the quality levels inside the acceptable limits.

Thanks to this modular adaptable signal processing system that can operate to RAMI standards on the edge and a strong interaction with data space and simulation tools, it will be possible to detect anomaly, reduce reject rate, increase Overall Equipment Effectiveness by adjusting the parameters in real time, reducing overall cost. This implies near-real-time co-simulation of manufacturing systems as a fully integrated "service" of a CPSoS. The development, commissioning and operation of DT, at different scale from a single product to the whole plant will be eased. Digital Twins make it possible to assess a SoS virtually before having it physically (DT working in the past), can monitor the actual status of the SoS (DT working in the present), or can be used to simulate a potential future condition applied to the SoS to plan the optimal use of the twinned asset (DT working in the future). The goal is to provide complex simulation environment (at both HW and SW level) and tools able to test, know the operation of certain systems or anticipate problems with simulation and human-centric visualization services. These simulation services make it easier to know what kind of answers can be offered in certain situations, without any physical risk for humans or machines.

Therefore, one of the main expectations of future autonomous factories is the use of digital twins with such cognitive capabilities in combination with human expertise. This will enable to leverage the capability to observe and monitor with high fidelity the behaviour of their respective physical twins, taking into consideration technical, economical and human perspectives. In order to make it happen, Cyberfactory will need to combine digital twins, which are driven by human expert and/or simulation-based domain models (i.e. knowledge), with the models derived from data (i.e. experience).

5.3.3. Anomaly Detection

5.3.3.1. Overview

Anomaly detection is the process of determining whether an observation in data conforms to expected behaviour.[394] Nonconformities in expected behaviour may be described in several ways, such as exceptions, outliers, contamination or, more commonly, anomalies. Data generated by a system running under normal circumstances may be considered to be representative of the state of the system, and erroneous changes in system state may be reflected by anomalies data outputs. Identifying these anomalies may prove useful in detecting erroneous system states.[395]

Techniques to determine if an observation is anomalous are typically based on creating models to make predictions on samples, working on the assumption that the underlying process will remain unchanged.[395] The number and types of variables within the source data determines the applicability and effectiveness of different anomaly detection techniques, and different anomaly detection techniques have varying effectiveness in given applications.[394] This creates a challenge for implementing anomaly detection in a system, where the viability, effectiveness and shortcomings of different approaches must be considered.

Chandola, Banerjee and Kumar[394] describe types of anomalies that can be detected. Three types are defined: point, contextual and collective. Point anomalies are data points that have qualities that differ significantly with respect to the rest of the data. A contextual

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[394] Chandola, V., Banerjee, A., & Kumar, V. (2009). Anomaly detection: A survey. ACM computing surveys (CSUR), 41(3), 1-58.

[395] Mehrotra, Kishan G., Chilukuri K. Mohan, and HuaMing Huang. *Anomaly detection principles and algorithms*. New York, NY, USA:: Springer International Publishing, 2017.

anomaly is a data point with properties that are anomalous based on the relationship between particular attributes. For contextual anomalies, attributes are split between those that are contextual, defining a basis for comparisons, and those that are behavioural, determining the measure to use in determining anomalies. A collective anomaly is a when a number of data points share properties that, individually, would not necessarily be considered anomalous.

Mehrotra, Mohan and Huang[395] further explain the difficulties in anomaly detection. The nature of the problem refutes a simple application of a classification technique, to predict a sample as anomalous or normal. Reasons for this include the rarity of anomalous events, the unpredictability on the anomalous characteristics and difficulty in determining thresholds for identifying an anomaly.

Using samples of known anomalies to create a prediction model would provide a simple mechanism to implement anomaly detection. However, obtaining labelled historic data is often prohibitively expensive. If the expected values for normal data can be defined, outliers should able to be detected by comparison, yet due to the nature of source data, including unknown or unpredictable data attribute values, it is difficult to predefine values of data variables that constitute anomalies. Instead, generic approaches are considered for constructing a prediction model. Three categories of models for anomaly detection exist, related to availability of labelled data. If labelled data is available, supervised algorithms can be employed, using the previously identified anomalous samples to clearly define what properties constitute an anomaly. If no labelled data is available, unsupervised algorithms can be used to detect anomalies, usually operating on the assumption that normal data is more common. If some data is labelled, semi-supervised learning algorithms can be used, garnering some benefits of supervised learning with reduced cost.[394]

5.3.3.2. Trends in Anomaly Detection

Detecting anomalies in data is accomplished through various techniques employing different types of algorithms. Anomaly detection techniques can be logically categorized based on the technique used to define an anomaly. Categories for anomaly detection techniques are: classification-based, neighbourhood-based, clustering-based, statistical, information theoretic, or spectral.[394,396]

Classification-based techniques assume a classifier exists that distinguishes anomalous data. These techniques make use of labelled data to create a prediction model to classify new data samples. Techniques in this category include neural networks, Bayesian networks, support vector machines and rule-based approaches.[394]

Neighbour-based techniques assume that normal data form dense neighbourhoods on the values of their attributes. Neighbourhoods are defined as volumes of plotted data points that have significant density with respect to all data points. Distance can be measure in various ways, such as Euclidean distance, matching coefficients or with similarity computations. Anomalies may be identified directly based on a data sample's distance to its k^{th} nearest neighbour, or by the relative density in the area of a data sample.

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[396] Ahmed, Mohiuddin, Abdun Naser Mahmood, and Jiankun Hu. "A survey of network anomaly detection techniques." *Journal of Network and Computer Applications* 60 (2016): 19-31.

Clustering-based techniques assume that normal data form clusters, while anomalous data will not be within the same boundaries. These techniques have no basis for directly detecting anomalies, relying heavily on the core assumption. Algorithms in this category include self-organizing maps, expectation maximization and k-means clustering.[394]

Statistic-based techniques assume that normal data occurs in high-probability regions of stochastic models. Existing data is fit to a statistical model and new samples are tested against the model. Techniques in this category include Gaussian or regression models, histograms and kernel functions.

Information-theoretic techniques assumes that anomalies induce irregularities in information content. These techniques define that the minimal subset, ***I***, of all data instances, ***D***, that maximizes C(***D***) – C(***D-I***) is anomalous, where C(***D***) is a measure of the complexity of the entire data set.[394]

Spectral techniques assume that subspaces (projections, embeddings, etc) will make anomalies easier to detect. These techniques attempt to simplify the problem of detecting an anomy. Principal component analysis is a core approach for performing spectral anomaly detection.[394]

5.3.3.2.1. Application Domains

Anomaly detection has been applied in many domains, including network intrusion, fraud, medical and public health, sensor networks, image processing, communications and factories. Current practices in domains overlapping with those of the Factory of the Future will be explored here.

Economic, Financial and Supply Chain

Camossi, Dimitrova and Tsois[397] investigated the applicability of anomaly detection techniques in a domain affecting the world economy. With 90% of world trade being, at some point, shipped in a cargo container, it is infeasible to manually investigate each container for anomalous activity, e.g. illegal trade. Their approach used unsupervised one-class support vector machine classification to read container status messages to find irregularities in container itineraries. The architecture of their work is shown below.

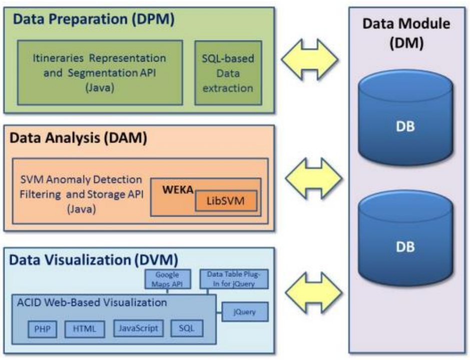

Figure 61: Anomalous Container Itinerary Detection Architecture[397]

[397] Camossi, Elena, Tatyana Dimitrova, and Aris Tsois. "Detecting anomalous maritime container itineraries for anti-fraud and supply chain security." *2012 European Intelligence and Security Informatics Conference*. IEEE, 2012.

Their results yielded from 99.769% to 99.986% with various system settings. The authors comment that further work should explore using different anomaly detection algorithms while considering scalability of feature selection, as high dimensional data is a challenge for anomaly detection.

Systems for detecting anomalies with payment cards have been historically very successful, with while fraud detection for bank card transactions suffers from false positives.[409] Thiprungsri and Vasarhelyi discuss using clustering techniques in accounting data related to insurance claims.[398] Their approach employed the k-means clustering algorithm with two attributes and eight clusters. Findings suggested that sparsely populated clustered represent data points with unusual characteristics are candidate anomalies. However, since the model operates on unlabelled data, each potential anomaly would need verification.

Cybersecurity

Makani, Ruchi and Redi investigate the application of different approaches to anomaly detection in mobile ad-hoc networks for cyber-security.[399] They find that both supervised and unsupervised techniques have been successfully deployed for cyber-security applications, yet argue that selection of a specific model should be made carefully. Hybrid models that employ multiple techniques are preferred over models using a single technique. Specific to mobile ad-hoc networks, Makani et al. provide a high-level overview on the performance of different machine learning techniques for anomaly detection.

Approach	Suitability in MANETs			
	Samples size Requirement	Accuracy	Training time	Resource Requirement
Artificial Neural Network	High	Very High	Very High	High
Bayesian Network	High	High	Low	Very High
Markov Model	High	Very High	High	High
SVM	Too Small	Very High	Low	Low

Table 8: Makani et al. Results of anomaly detection approaches with machine learning.[399]

Security operations anomaly detection is detailed further by Yao et al, separating different security considerations into levels of a pyramid.[409]

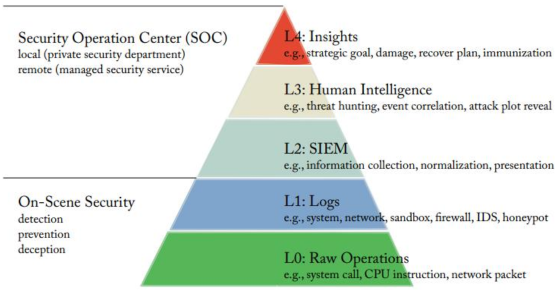

Figure 62: Security Pyramit from Yao et al.[409]

[398] Thiprungsri, Sutapat, and Miklos A. Vasarhelyi. "Cluster Analysis for Anomaly Detection in Accounting Data: An Audit Approach." *International Journal of Digital Accounting Research* 11 (2011).
[399] Makani, Ruchi, and B. V. R. Reddy. "Taxonomy of machine leaning based anomaly detection and its suitability." *Procedia computer science* 132 (2018): 1842-1849.

Technical solutions for detecting cyber-security related anomalies will typically apply at the L1 and L2 layers. This domain of anomaly detection is highly competitive and there are many offerings from different vendors for solutions.

Layer 1 anomaly detection is generally characterized as being singly focused, without consideration for correlation between measures or features to determine anomalies. For example, a system may detect an anomalous CPU utilization or high memory consumption, but may not be expected to correlate the behaviour of these two features together.

Vendor	L1 Product	Anomaly
Avast	Antivirus	Program behavior
Fortinet	Intrusion prevention system	Protocol
LogRhythm	User and entity behavior analytics	Endpoint
ManageEngine	Applications manager	Performance
RSA	Siver Tail	Network
Silicon Defence	Statistical packet anomaly detection engine	network packet
SolarWinds	Snort IDS log analysis	network

Table 9: Yao et al.: L1 Anomaly Detection Products or Services

L2 technologies expand on the capabilities of L1, allowing for aggregation and correlation. As is often an issue with anomaly detection, more data is not necessarily better, as higher dimensional space increases computational effort in creating models and may be detrimental to the accuracy of results. Many products are available from various vendors for L2, shown in the below table. L3 and L4 involve aspects of human intervention, planning and strategy for which there are no generic technical solutions.

Vendor	L2 SIEM Product	Anomaly Detection Emphasis
EventTracker	Security center	General behavior analysis
HPE	ArchSight	Peer group analysis
IBM	QRadar	Traffic behavior analysis
LogRhythm	LogRythm	User and entity analysis
Micro Focus	Sentinel Enterprise	Environment analysis
Splunk	Enterprise security	Statistical and behavioral analysis
Trustwave	SIEM Enterprise	Network behavior analysis

Table 10: Yao et al.: L2 Anomaly Detection Products or Services

Cyber-Physical Systems

Yao *et al.* discuss the problem of anomalies in cyber-physical systems, where anomalies in systems have more serious consequences due to the physical component of these systems.[409] At the same time, opportunities for detecting anomalies in CPS are increased, since there is possibility for detection on either the cyber or physical layers. Accordingly, there are three categories of anomaly detection for CPS: cyber, physical or cyber-physical models.

Operating under a threat model, there are two categories of attacks against a CPS: control-oriented or data-oriented. Control-oriented attacks attempt to divert program flow in a system. Data-oriented attacks attempt to manipulate a system's decision-making process by changing data that the system relies on.

Yao *et al.* categories recent research on anomaly detection in cyber-physical systems as shown in Table 1. The underlying technique for each research effort was highlighted where possible to show the relationship between new effort and the categories presented by Chandola, Banerjee and Kumar.[394]

Research	Category	Focus	Technique(s)
C-FLAT[400]	Cyber	Control-oriented attacks.	Rule-based
Yoon et al.[401]	Cyber	Frequency-based program control flow anomaly.	Clustering
Feng et al.[402]	Cyber	Traffic alteration.	Time-series
Zimmer et al.[403]	Cyber	Code injection.	Rule-based
Hadziomanovic et al.[404]	Physical	Data injection.	Statistical and rule-based
Cardenas et al.[405]	Physical	Data injection.	Time-series
SRID[406]	Physical	Data injection.	Novel: state-relation graphs.
C2[407]	Physical	Control signal violation.	Rule-based states.
eFSA[408]	Cyber-Physical	Data-oriented attacks.	Novel: finite state graphs.

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400 Abera, Tigist, et al. "C-FLAT: control-flow attestation for embedded systems software." *Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security*. 2016.
401 Yoon, Man-Ki, et al. "Learning execution contexts from system call distribution for anomaly detection in smart embedded system." *Proceedings of the Second International Conference on Internet-of-Things Design and Implementation*. 2017.
402 Feng, Cheng, Tingting Li, and Deeph Chana. "Multi-level anomaly detection in industrial control systems via package signatures and LSTM networks." *2017 47th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*. IEEE, 2017.
403 Zimmer, Christopher, et al. "Time-based intrusion detection in cyber-physical systems." *Proceedings of the 1st ACM/IEEE International Conference on Cyber-Physical Systems*. 2010.
404 Hadžiosmanović, Dina, et al. "Through the eye of the PLC: semantic security monitoring for industrial processes." *Proceedings of the 30th Annual Computer Security Applications Conference*. 2014.
405 Cárdenas, Alvaro A., et al. "Attacks against process control systems: risk assessment, detection, and response." *Proceedings of the 6th ACM symposium on information, computer and communications security*. 2011.
406 Wang, Yong, et al. "Srid: State relation based intrusion detection for false data injection attacks in scada." *European Symposium on Research in Computer Security*. Springer, Cham, 2014.
407 Stephen McLaughlin. CPS: Stateful policy enforcement for control system device usage. In Proc. of the 29th Annual Computer Security Applications Conference, (ACSAC'13), pages 109–118, 2013. DOI: 10.1145/2523649.2523673. 56
408 Cheng, Long, Ke Tian, and Danfeng Yao. "Orpheus: Enforcing cyber-physical execution semantics to defend against data-oriented attacks." *Proceedings of the 33rd Annual Computer Security* Applications *Conference*. 2017.

Table 11: Research in CPS Anomaly detection[409]

5.3.3.3. Tools and Services

There are a free or open source projects available for implementing anomaly detection. Tools exist for developing customized solutions. Table 2 outlines available tools, libraries or frameworks while Table 3 shows available programs and projects.[409]

Tool, Library or Framework	Description	Reference
Weka	Open source software providing machine learning algorithms for standard tasks. Provided as a Java API, graphical interface or terminal application. Licensed under GNU General Public License.	https://www.cs.waikato.ac.nz/ml/weka/
ELKI	Java data-mining software with a focus on unsupervised clustering analysis and outlier detection. Licensed under GNU Affero General Public License.	https://elki-project.github.io/
Scikit-Learn	Python package that provides machine learning tools for data analysis. Licensed under New BSD License.	https://scikit-learn.org/stable/
TensorFlow	Python and C++ libraries providing state-of-the-art machine learning tools. Licensed under Apache License 2.0.	https://www.tensorflow.org/

Table 12: Tools for creating anomaly detection projects

Program or Project	Description	Reference
Apache Spot	Anomaly detection platform targeting network intrusions using machine learning.	https://spot.apache.org/

[409] Yao, Danfeng, et al. "Anomaly detection as a service: challenges, advances, and opportunities." *Synthesis Lectures on Information Security, Privacy, and Trust* 9.3 (2017): 1-173.

Program or Project	Description	Reference
	Licensed under Apache License 2.0.	
Open Source Tripwire	Program providing file integrity anomaly detection. Licensed under GNU General Public License.	https://github.com/Tripwire/tripwire-open-source
OSSEC	Host-based cybersecurity anomaly detection for various operating systems. Licensed under GNU General Public License.	https://www.ossec.net/
OSSIM	Platform (virtual machine) that offers a variety of solutions, including intrusion detection and behavioural monitoring. Licensed under GNU General Public License.	https://cybersecurity.att.com/products/ossim
Apache Metron	An open-source framework designed to provide the ability to detect and respond to cyber anomalies. Licensed under Apache License 2.0.	https://metron.apache.org/
Security Onion	Security Onion is a collection of tools for security monitoring, log management and analysis. Each tool operating under with their own licenses.	https://securityonion.net/
Splunk	Data analysis tool working with arbitrary machine data. Can be used to apply generic machine	https://www.splunk.com/

Program or Project	Description	Reference
	learning algorithms for identifying anomalies. Splunk operates with a paid license with trial period.	
Anomaly Detection (R Package)	A statistically robust R programming package designed to detect anomalies. Uses Seasonal Hybrid ESD (S-H-ESD) to detect anomalies. Useful for both time series data and feature vectors. Licensed under GNU General Public License.	https://github.com/twitter/AnomalyDetection
EGADS	Java package performing anomaly detection on large time-series datasets, with applications in cybersecurity contexts. Licensed under GNU General Public License.	https://github.com/yahoo/egads
Surus	Pig and Hive scripts implementing robust anomaly detection, utilizing principal component analysis. Licensed under Apache License 2.0.	https://github.com/Netflix/Surus

Table 13: Open source or free anomaly detection programs

5.3.3.4. Anomaly Detection in the Cyberfactory

A successful implementation of anomaly detection revolves around the resulting confusion matrix with measures of accuracy, precision, recall and F1 score.

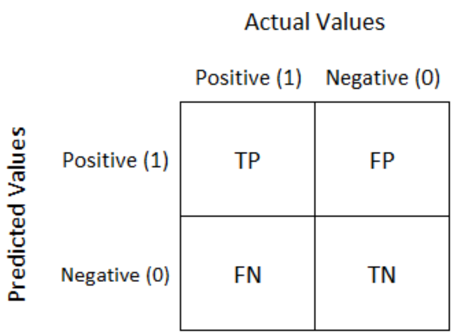

Figure 63: Confusion Matrix

For a system to perform well, we can borrow concerns from related fields to highlight areas that need to be addressed when creating an anomaly detection system. Garcia-Font, Garrigues and Rifà-Pous[410] discuss efforts of anomaly detection in smart cities – an environment not too dissimilar from a factory of the future. An argument is made that, while machine learning techniques perform well, there is no simple approach to selection and implementation.

They list the following as primary challenges:

- Models: One versus Many
  - There exists a trade-off in efficiency and accuracy when creating models to predict anomalies. Each context may warrant and individual model, even if analysing the same data but with a different feature vector.
- Choice of Technique
  - Each technique to create a prediction model may have varying performance (e.g. confusion matrices) under different contexts. Multiple techniques should be available within an anomaly detection platform to allow selection (automated or otherwise) of the best fitting model.
- Unnoticed attacks or malfunctions
  - Anomaly detection can only be as good as the data available to the system. If there are no data artifacts generated from an attack or malfunction, then the anomaly detection system will provide no value. The factory of the future is expected to have an abundance of data, yet no assumptions should be made on data availability.
- Training data
  - Some techniques for creating prediction models depend on clean data. If data is contaminated with anomalous samples, the results may be unpredictable. This is a separate area of research related to robust or adversarial training.
- Data aggregation

[410] Garcia-Font, Victor, Carles Garrigues, and Helena Rifà-Pous. "Difficulties and challenges of anomaly detection in smart cities: A laboratory analysis." *Sensors* 18.10 (2018): 3198.

- If raw data is aggregated (e.g. by time), then the resulting predictions may be less accurate. It is up to the team implementing anomaly detection to carefully consider the implications of the quality of data being used as input into an anomaly detection system.

Ultimately, the success of an anomaly detection system within the factory of the future will depend on the cross-disciplinary expertise of the team involved. Applicable techniques and models must be considered by those with knowledge of data sciences while important features should be identified by those with more operational knowledge. Ideally, a system should be versatile in availability of techniques and the number of models to allow user to tune the system to their needs according to the data quality and availability.

5.4. Summary: Cyberfactory Approach to SoS Simulation

System of systems (SoS) is therefore the viewing of multiple, dispersed, independent systems in context as part of a larger, more complex system. The goal of an SoS architecture is to get maximum value out of a large system by understanding how each of the smaller systems work, interface and are used. Such designs require systems thinking -- a holistic approach to analysis that focuses on the way constituent parts interoperate, work over time and function within the context of a larger, evolving system. The SoS approach promote a new way of thinking for solving grand challenges where the interactions of technology, policy and economics are primary drivers.

The CyberFactory#1 project will integrate different systems obtained in the previous systems modelling in Cyberfactory into a common SoS model and simulation. This SoS modelling will simulate the use cases and will also enable the interactivity between all of them, which will affect in terms of capital inputs, production estimations etc. In order to build the systems that are going to represent the different use cases, all will begin from the same template, enabling to integrate the similar characteristics that compose the systems:

- The CPS that the use case needs for the development of its product/service.
- The required ecosystem and settings that each use case needs for defining the environment.
- The Human behaviour that reflects workers in the use case.

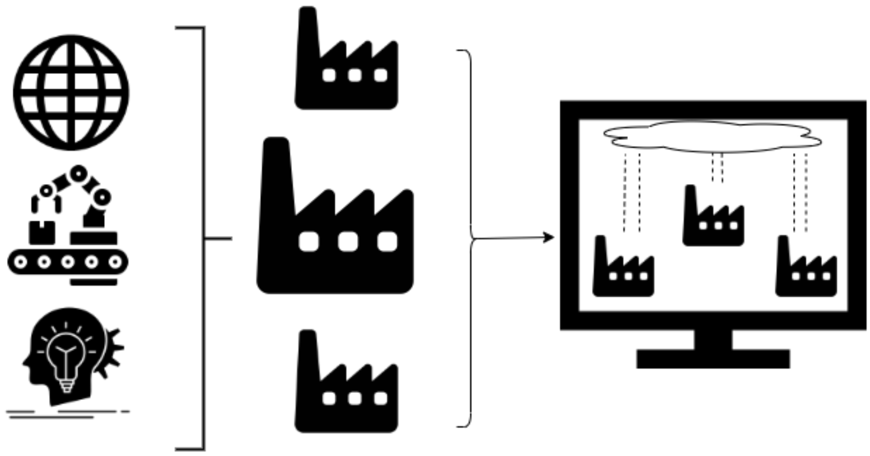

Figure 64: SoS organization.

The results that are brought out from this SoS simulation are different to the ones obtained by other tasks: the functionality of the SoS is indeed to offer more than each system added with each other. This is possible because of the interaction between systems (whether different -e.g. CPSs and human behaviour-, or with the same characteristics -e.g. CPS and CPS), where new, not-predicted results may arise.

The SoS has to represent an environment in which all the systems that are integrated interact with each other. However, these interactions among systems have to be set up and defined first. Answering these questions will enclose the necessary algorithm for data processing in this SoS. The data that will be implemented in the SoS will be processed as a single model, obtaining the corresponding results (similar results from previous tasks), and as an interactive model, obtaining new results.

Depending on the number of systems that are integrated there will be more results or less, due to the level of interaction. The more interactions are taken into account, the more results can be extracted from the simulation, and the more the SoS simulation is similar to the reality and useful to optimise the functionality of the use case. However, with each added interaction, the simulation becomes exponentially more complex, adding great cost in computational capabilities and for modelling and simulating.[411] A balanced, optimal point must therefore be achieved.

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[411] http://www.lix.polytechnique.fr/~golden/systems_architecture.html#principles