DESIGN OF CRUCIAL ELEMENTS FOR INDUSTRIAL PLANTS, OFFSHORE PLATFORMS AND UNDERWATER FACILITIES

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ABSTRACT
The paper proposes some specific models to be used in design of crucial elements for Industrial Plants that previously were not easy to be addressed by simulation due their functional complexity. As examples of these kinds of elements are proposed autonomous systems for fire fighting and/or emergencies for on-shore and off shore plants as well as equipment for underwater operations. The paper proposes use of MS2G Simulation Paradigm (Modeling, interoperable Simulation and Serious Games) as solution in these specific cases to test concepts and capabilities.

Keywords: Industrial Plant, Off-Shore Platforms, On-Shore Infrastructures, Underwater System, Simulation

1 INTRODUCTION
Design of specific components in modern industrial plants is sometime quite difficult, especially in cases where major complexities are present; in particular, it is important to outline two principal typologies of complexities that correspond specifically to internal complexity and interactions among components.
In case of internal complexity, we have usually to deal with systems characterized by complex physical phenomena, in these case the solution of differential equation could result critical as well as the influence of boundary conditions and control systems; for instance, very good examples are proposed by systems including chemical thermo-dynamics or mechanics of cables under specific boundary conditions (Ablow et al., 1982; Reverberi et al.,2016; Bruzzone et al.,2017a; Buckman et al., 2004). The second typology of problems is represented by systems where several different objects interact dynamically and their mutual interference result difficult to be represented without simulation; a very good example is related to interaction among vehicles and handling devices in production plant or in operations (Williams et al., 1997; Smith 2013; Baruwa & Piera 2016). These cases are common in Industrial Plant Engineering over a wide spectrum of systems and components and traditionally there are procedures to support the design based on specific assumptions; the use of simulation in this cases represent the most effective approach, however, in the past there were some difficulties in cases when development of models and solutions for industrial applications was constrained by limited time and resources (Fowler & Rose 2004). From this point of view, the Lean Simulation approach results very effective and could be the proper solution for this problem (Bruzzone & Saetta 2002). In this paper the authors propose to combine Lean Simulation with MS2G (Modeling, interoperable Simulation and Serious Games) in order to create immersive, usable and intuitive simulation systems able to support interactively the design of new plants, new facilities and/or new components in complex systems (Bruzzone et al., 2014).

2 LEAN SIMULATION AND MS2G FOR PLANTS
In facts, the Lean Simulation deal with development of specific models starting from “model templates” customized on specific application fields which could be tuned quickly by small team of experts (Amico et al., 2000; Balci 2004). These teams are expected to use Design of Experiments in pragmatic way to face criticalities and to complete quickly validation, verification and preliminary analysis. By this approach fidelity level and confidence band of simulators are relaxed in order to speed-up developments, tailoring and analysis (Bruzzone & Saetta 2002; Tiacci, Saetta & Martini 2003); however, the Lean Simulation Protocols guarantee to keep variance under control and to be aware of tolerances as well as about the assumption hypotheses. By this approach, the VV&A (Verification, Validation and Accreditation) could be standardized on the specific sectors in order to be complete quickly; by the way one of the major advantages by this simulation development process is the capability to obtain quickly results in real industrial cases. From this point of view, the use of MS2G Paradigm is very promising because it enables two major properties: “interoperability” and “usability” (Bruzzone 2017). In facts the interoperable simulation allows to combine different models representing for instance different plant components, systems or subsystems; concurrently the adoption of Serious Game approach enhance the engagement of users within intuitive, immersive, interactive environments that could provide an effective and efficient way to test different design solutions and to support industrial plant engineering as it has been done in education for engineers (Bruzzone et al.,2016; Longo et al. 2017; Baghirolli et al., 2016).

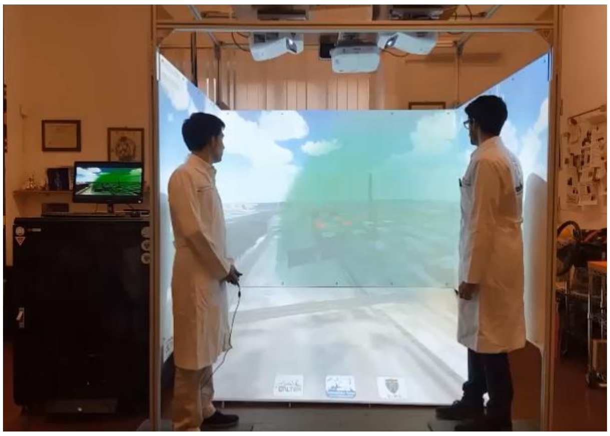

Figure 1. Hazardous Material Spill Simulation in a Plant

The opportunity to use simulation as support tool was evident since many decades, however, limitations caused by available methodologies, techniques and computational power, in some cases forced development of simplified approaches or models for complex processes. For instance, in 80's the computational fluid dynamics was already known, but available to relatively small number of big organizations, while nowadays such calculations could be performed on most of the consumer personal computers (Witherden & Jameson 2017). From the other side, increasing complexity of systems of interest requires the M&S researchers and developers to create more and more sophisticated models. One of reasons of constantly increasing complexity is related to the changes in processes and machines of interest, which, for example, could be caused by implementation of a new process with higher precision and bigger number of steps. Another important reason of increasing of complexity of systems of interest is related to their architecture and interactions. For example, in case of an industrial plant simulation, in order to estimate efficiency of the future system it could be necessary to consider management of a warehouse of raw materials and final products, physics of processes in production lines, influence of stochastic events on efficiency of machines and on the personnel (Merkuryev et al., 2010). Another example of complex model is related to the plant providing such services as Incineration of urban solid waste. In fact, many big and medium cities are now interested in implementation of these solutions and into combining them with Smart City paradigm, which allows to improve efficiency of the town by acquiring in real time a lot of available data related to the city's state from different sources; obviously in this case the next step is often related to support decision making by simulation, which allows to analyze situation and estimate potential alternative policies respect planned or proposed activities (Bruzzone et al.,2014). In this case the model should consider interactions between different independent systems, such as population demand and behavior, logistics transportation network, power grids, meteorological conditions, hence, such situation is closer to System of Systems (SoS) rather than to just a single one (Bruzzone et al.2017c).

For these reasons, in order to satisfy current and future requests of the industry, it is necessary to be able to develop not only very complicated models of single systems, but new methodologies able to couple different models that could support design and engineering. In the following some case studies are proposed to confirm the validity of this approach.

2 ONSHORE PLANT

In Industrial plants in case of emergencies it is necessary to adopt special procedures addressing often such emergency procedures as fire-fighting and contamination containment. The proposed case is related to industrial plants that could release contaminants due to spill of hazardous material in atmosphere. In facts the safety engineering focuses on identification, selection and design of proper solutions in order to to guarantee human safety as well as to reduce vulnerability of the plant. In this case there is a strong relation between the physical phenomena dealing with contamination, including transport of contamination agent due to wind, influence on toxicity level of different boundary conditions inhomogeneous respect the area and time evolution (e.g. temperature, luminosity, humidity), etc. In addition, it should be stated that there are innovative systems devoted to support operations in case of crisis; for instance, the proposed case deals with UAV (Unmanned Aerial Vehicles) devoted to carry operations indoor and outdoor the plant with special attention to collection of data related to contamination level in order to monitor situation, identify dangerous area and delimit the perimeter. In this case the model for contamination was developed to be interoperable with the UAV simulators just to test the effectiveness of these systems to operate in the complex environment as well as to be responsive respect criticalities due to changes in boundary conditions or crisis evolution (Bruzzone et al. 2015). In the proposed case we developed specific models devoted to reproduce the dynamic of the spills, the transport, the diffusion, the precipitation, the ground contamination, etc.

These models have been based on particle approach using differential equations for each element behavior combined with empirical fuzzy sets to estimate contamination level (Bruzzone et al. 1996). These models are able to run in real time with relaxed fidelity and to interoperate with the simulator of the UAV, as shown in figure 1, where is proposed the augmented reality used to present the contamination evolution to allow designer to check efficiency of UAV system.

It is interesting to state that, as proposed in this picture, the designers and engineers could easily operate these models within a CAVE (Cave Automatic Virtual Environment); for instance in this example they use the SPIDER (Simulation Practical Immersive Dynamic Environment for Reengineering) developed by Simulation Team.

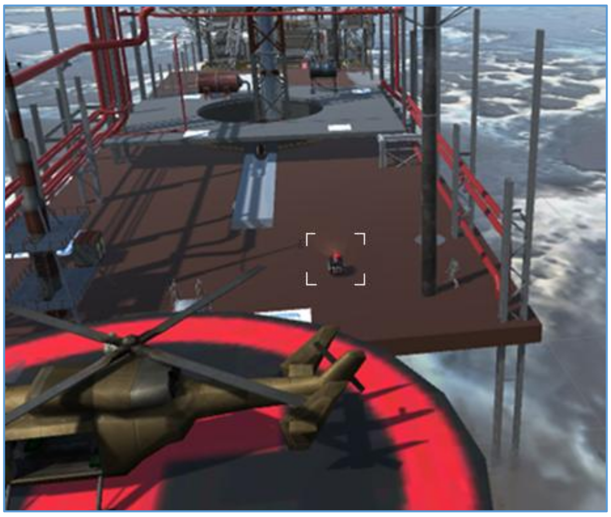

Figure 2. Simulation of Fire Fighting UGV for Off-Shore Platform

This capability emphasizes the Interactive and Interoperable aspects thanks to the special design of SPIDER that integrates up to six big touch boards (4 screens 2m x 1.5 m in proposed picture) within a compact "centripetal cube" (just 2m x 2m x 2.6m).

3 OFFSHORE PLATFORMS

In this case the problem addresses the design of a new specific system devoted to support operations on OffShore Platforms; in this case the system is an UGV (Unmanned Ground Vehicle) with a robotic arm able to control a fire hose and to operate in too dangerous areas for the people on board of the platforms in case of fire (Bruzzone & Figini 2004). In this case the robotic system design is complicated by the necessity to consider its capability to move and operate in complex environment and to interact with the fires as well as with other equipment; so concurrently to classical design approach to define power, weights, geometry of the UGV there is a real need to create an interactive immersive virtual world where to test different configurations and to identify best alternatives (Bruzzone et al.,2017d). In this case the adoption of MS2G is very promising considering that it allows to check mobility, interference and capabilities of chosen solutions. In this case the authors created a model using IA-CGF (Intelligent Agent Computer Generated Forces) logic and used a synthetic environment based on SO2UCI (Simulation for Off-Shore, On-Shore & Underwater Critical Infrastructure). This synthetic environment was originally developed for training of plants operators and principally devoted to security of Off-Shore Platforms (e.g. oil rig, gas rig), On-Shore Critical Infrastructures (e.g. power plants, refineries, ports) and Underwater Critical Infrastructures (e.g. cables, pipelines). SO2UCI includes models of different systems including autonomous and traditional vehicles, for example Rigid Hull Inflatable Boat, Helicopters, Sensors, UAV, Unmanned Surface Vehicle, Autonomous Underwater Vehicles (AUV), Gliders, etc. This a good example of MS2G that support interoperability through High Level Architecture. In facts this approach could be used in design and engineering to check the different alternatives on the simulator and eventually to test also interactions of the whole new robotic system, through hardware in the loop, with other real equipment, controls or sensors. In figure 2 is proposed the output of the simulator reproducing the dynamics the robotic system while it move over the off-shore platform.

4 UNDERWATER SYSTEMS

In some of industrial fields many crucial operations are performed in quite hostile environments, such as deep water, which is characterized by high pressure, low visibility and low temperature (Shukla et al.2016). In some cases, the risks of such activities could be carried out by autonomous systems, however, despite the advances offered by the new robotic systems, humans are still required due to higher flexibility in many of underwater operations. Hence, due to the risk of accidents, errors, mistakes and consequential injures of divers and damage of costly equipment, this simulation allows to support design and tests. So, it is clear that engineering support from M&S (Modeling and Simulation) is crucial in activities that deal with Oil and Gas Underwater Facilities. In addition, these aspects could be also very useful to support training activities, reduce costs and risks by substituting the real plant or equipment with a properly verified and validated simulators (Bruzzone et al., 2017b; Longo et al. 2015).
One of most crucial activities in this field is the life-support supervision of deep water divers that requires support vessels interacting dynamically with hyperbaric chambers and diving bell; the proposed case faces the necessity to models cable connections and their dynamics considering that major part of them are underwater, connected with different elements moved by waves (support vessel), current (diving bell) and interacting with the underwater plant components. The cables provide power, communication, but what is especially important, breathing gas mixtures; in fact, a crucial risk in deep water activities in general, is related to proper management of special gas mixtures, as well as to control their pressure and temperature (Shilling 2013); so it is evident that cable behavior could affect several aspects of operations and influence systems and subsystems' efficiency and reliability (Buckman et al., 2004); due to these reasons it is important to model these elements as happen since long time (Ablow et al., 1982). So the Life-Support System supervision and control to operate diving bells could require creation of models of these systems which considers their interactions; by the way it is important to outline that these models could be effectively used also to consider other kind of equipment for underwater facilities at higher deeps such as Exosuits and ROV (Remotely Operated Vehicle) where the cable transmits only power and data; finally also AUV (Autonomous Underwater Vehicles), supposed to be adopted in future in these

field and to be free from cables for power and data, could also benefit of these simulation models, in facts there are hypotheses to equip them, in some case, with special new optical fibers, which allow to transmit data faster and with less losses respect to acoustic modems. These models have been tested in several applications (Bruzzone et al.,2017b, 2017d). The dynamic models of marine cables could be based on creating an interactive link of dynamic elements; in fact, these cables are widely used in the ocean environment to manage power, communications, transport of the gas mixture and even just to lift the equipment (Buckman et al., 2004). This case proposes two problems in the dynamic analysis of the cable. First, when the tension is zero, which is often the situation encountered, the geometry of the cable becomes a singular matrix that need to be addressed. Second, the transformation from local coordinates to global coordinates, through Euler angles, leads to quite a great number of unknown variables that could be corresponding to equivalent configuration of the cables respect known positions and constraints; these elements produce quite complex differential equations, so it is necessary to compute them and to add specific elements that represent physical constraints.

For instance major aspects are related to the mechanical characteristics such as bending stiffness of the cable; in addition to identify suitable configurations respect previous one and their dynamics respect different solicitation provided by internal and external forces, it result necessary to apply hypotheses on different fixed points; for instance the action of the boat motion affect the cable and transfer through it forces to the diving bell, but at the same time the current on diving bell affects the cable and also the boat; same concept applies to the diver connected by umbilical cable to the diving bell and vice versa. Obviously an iterative procedure based on computational integration of differential equations could introduce inconsistencies and singularities in the resolution of the problems.

So it is necessary to develop specific methodological approaches able to create an effective consistent three-dimensional model of the dynamics of marine cables. A point already mentioned, it is that the model should take into account the bending stiffness of the cables to overcome the singularities in the geometric stiffness matrix, in order to overcome any problem related to use of Euler angles. Therefore, it is also necessary to define an approach to introduce ad hoc displacement: in this way the displacement uses a differential that allows to estimate the curvature geometry and the torsion and allows to establish the transformation from the local coordinates to the global ones in consistent way.

In facts, as already mentioned, the general formula of marine cable dynamics could be applicable to a wide range of cases such as wires and ropes, but must be tested in terms of resolution, fidelity and computational efficiency to guarantee fast time and real time simulation as necessary to support engineering. All the models should be designed to address the dynamic evolution in 3D based on the differential equations. By adopting the Lean Simulation approach, it is possible to accept quite bland fidelity of this model providing in any case very valuable results for the engineering respect current simplified hypotheses. In facts by this approach it is possible, theoretically, to reconstruct the dynamic response of the cables respect to the motions of all elements including the ship as well as the effect of waves over different axis which affects speed and course. The three-dimensional solution must be computed on equations of motion as functions of Euler's angles by spatial integration using a finite element model, which uses a finite number of elements for temporal integration; in facts this approach is valid also to study the influence of transverse currents in the cable configuration.

The simulation of a virtual prototype of boat or vessel (including underwater elements such a submarine or a diving bell) requires special models to reproduce the motion stimulated by waves and generated by the buoyancy dynamics. In this sector complex models have been developed, which, however, sometimes are ill-suited for real-time simulations while they could be very useful for the detail aspect of naval engineering; in this case it is necessary to address some kind of balance between the fidelity of the cable virtual prototyping and the requirements to be able to run the simulator in order to support engineering.

In general, respect the effects of waves, usually, the models are based on a set of hull points that allows to consider the part immersed considering the Archimede’s forces along with that weights on the body; in addition it consider the impact of ship motion. In particular the models of sea are expected to keep into account the intensity of weather conditions and to reproduce the motion of ship, usually these results are quite complex and computational heavy in case of surface ships, while submerged bodies are easy to compute (no wave effects); considerations on the support vessels devoted to operate our equipment over underwater facilities simplify a little bit the problem considering that the focus is on the dynamics of the cables and that these one are just partially influenced by wave movements of the support vessels; so their fidelity is not very critical; however proposed approach could be extensively applied to a wide spectrum of surface entities.

In facts, as anticipated, the prediction of the ship's motions has always been a problem in the simulation of the ship's motion and in the evaluation of its impact on the on-board systems and sensors. In this regard, many models have been developed in the past to study this topic. On the other side the analysis of the systems and mechanisms subjected to these movements is very demanding, so usually for these simulations approximations relative to the elementary forms of movement are used. In this case it is expected to simulate the motion of the bell, but it could be valid also to support the design of cranes placed on the pontoon or support vessel considering the impact of their dynamics.

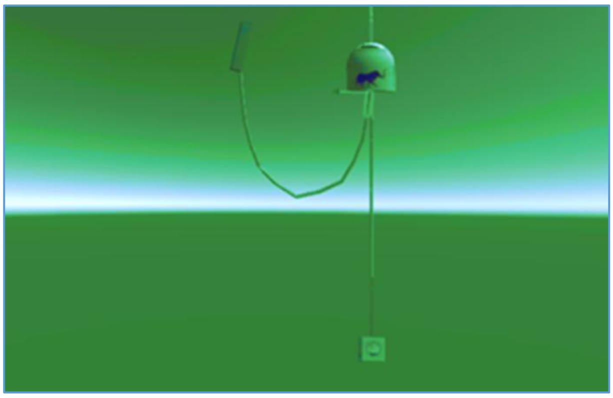

Figure 3 Simulation of Cable Dynamics for an Underwater System

Obviously it is critical to consider weather and boundary conditions (e.g. wind on surface infrastructures, current, waves) in order to reproduce sea keeping and motion. From a dynamic point of view this system is not very complex for underwater floating element (e.g. the diving bell) while the crucial aspect is the capability to mdoel the interactions on cable itself and its behavior. The sea model is based on Jonswap / Bertschneider functions reproducing the wave spectrum (Zini 1999). In this way it becomes possible to obtain different wave spectra corresponding to different values of the significant wave height, the peak wave period and the direction of the wave itself.
In this case it is necessary to define functions that returns the history of the six DOF movements (Degree of Freedom), speeds and accelerations of the marine element. It is convenient to leave up to the designer the possibility to interactively change the parameters of the simulator defining the wave profile (i.e. spectrum or frequency, wave height, direction angle) and characteristics of the marine vessel (e.g. course and speed); indeed, by this approach during design it is immediately evident the impact of the waves on support vessels as well as on the underwater equipment and its operations. From this point of view, the first step is to develop a 3D simulation of a marine operations and the 3D geometries of the vessels and the equipment of interest. In the proposed case, the 3D model of the ship can be obtained from the CAD system database where available. The Models of Cable and Floating are created by defining their volumes and weights; for instance, for the diving bell in this case the geometry is elementary consisting of a hemisphere superimposed to a cylinder. Bell buoyancy, like all the other models, is regulated by a physical engine (i.e. Unity Physx, Bullet) where the forces due to weight and Archimedes's principle are modeled as follows:

$$\boldsymbol{F_c(t)} = \begin{cases} \boldsymbol{h_c(t) \geq 0} & \boldsymbol{F_c(t) = -g \cdot m_c} \\ \boldsymbol{h_c(t)} < 0 & \boldsymbol{F_c(t) = g \cdot \left(V_c \rho_{H_2O} - m_c\right)} \end{cases}$$

For simplicity, a constant volume has been assumed, in reality when one is on the surface of the water one should use only the portion of immersed volume. Also the mass for simplicity has been assumed constant even if it varies according to the diversities inside.

The diver has been modeled in a simple way with a mass and volume similar to those of a human being. In the model it is connected via an umbilical cable to the bell while its flotation is regulated together with the remaining models by a physical engine where the weight and thrust of Archimedes are modeled as follows:

$$\boldsymbol{F_d(t)} = \begin{cases} \boldsymbol{h_d(t) \geq 0} & \boldsymbol{F_d(t) = -g \cdot m_d} \\ \boldsymbol{h_d(t)} < 0 & \boldsymbol{F_d(t) = g \cdot \left(V_d \rho_{H_2O} - m_d\right)} \end{cases}$$

It is important to underline that, being connected to the umbilical, which has its own mass and it is regulated by Archimedes's Principle, the diver is affected by several forces. Here too it should be mentioned that, similar to the model of the bell, volume and mass for simplicity are supposed to be constant.
The model of the ballast has been recreated defining its volume and weight in accordance with a real case where it is a block of concrete. This weight is connected, by a cable to the bell, with the difference that in this case it was assumed that this is just steel cable, while previous ones include also umbilical and power transmission lines.
The floatation of the ballast is regulated like all the remaining models through the simulation by physical engine, where the weight and Archimedes's Principle are summarized by following relationships:

$$\boldsymbol{F_z(t)} = \begin{cases} \boldsymbol{h_z(t) \geq 0} & \boldsymbol{F_z(t) = -g \cdot m_z} \\ \boldsymbol{h_z(t)} < 0 & \boldsymbol{F_z(t) = g \cdot \left(V_z \rho_{H_2O} - m_z\right)} \end{cases}$$

Similarly to the other models, the volume and mass of the ballast for simplicity has been assumed to be constant.
The ship present in the scenario has been recreated through an elementary geometry composed of several blocks scaled and interconnected between each other. The ship is connected by the cable to the bell that can be positioned at various depths (e.g. 200 meters below sea level). Its buoyancy is regulated differently than the other objects in order to have a fluctuation that considers the phenomenon of sea keeping linked to the wave motion without requiring too much intense integration of differential equations; so the model used in this case is structured as follows:
The mass assigned to the ship is subdivided in different hull points (e.g. corresponding to 4 elements at 3 different levels on the hull) and geometrically balanced so, in every moment, the simulator is able to consider how much each block is submerged and/or over sea level.
Depending on the position relative to the sea, a vertical force is applied to each single point defined as follows:

$$\boldsymbol{F_g(t)} = \begin{cases} \boldsymbol{h_{rel}(t) > l_s} & \boldsymbol{F_g(t) = -F_{down}} \\ \boldsymbol{l_s \geq h_{rel}(t)} > 0 & \boldsymbol{F_g(t)} = -\left|\boldsymbol{F_{down} \cdot \frac{h_{rel}(t)}{l_s}}\right| \\ \boldsymbol{0 \geq h_{rel}(t) > -l_s} & \boldsymbol{F_g(t)} = +\left|\boldsymbol{F_{up} \cdot \frac{h_{rel}(t)}{l_i}}\right| \\ \boldsymbol{h_{rel}(t) \leq -l_s} & \boldsymbol{F_g(t) = +F_{up}} \end{cases}$$

$\boldsymbol{h_{rel}(t) = z(t)_{point} - z_{mare}(x, y, t)}$ relative height between the hull point and the sea level in the coordinates x, y and at time t

$\boldsymbol{F_{down}} = \frac{g \cdot m_b}{n^{\circ}_{punti}}$ force weight of the vessel divided by the number of points taken into consideration (in this case 12)

$\boldsymbol{F_{up}} = \frac{g \cdot m_b}{n^{\circ}_{pgal}}$ force weight of the vessel divided by the minimum number of points that touch the water necessary for the ship to float (e.g. 8 over 12).

For instance in Figure 3, it is proposed a configuration of an Underwater System devoted to operate down to 300 m including a ballast, two divers interconnected by umbilical to a diving bell, the diving bell itself and the support vessel on surface (not visible on the figure, but interacting dynamically with others); all these elements are interconnected by different kind of cables with specific characteristics and reacting dynamically along simulation; this simulation run both in real and fast time and it was effectively implemented by Simulation Team using C# and Unity 3D while interoperability is based on a specific module in Java created at Genoa University.

CONCLUSIONS

The current paper proposes a quick overview on different MS2G approaches to support engineering of industrial plants and facilities; these models effectively reproduce complex systems and are virtual prototypes capable of interaction with users as well as with real hardware to test and evaluate design solutions.

Indeed, it is also possible to immerse the engineers within a CAVE to experience "from inside" the situations and to review all the technical reports on output and controlled variables; this supports engineering and allows to tune the system parameters. It is evident that these simulators should be intuitive and interoperable, but also to be completed in reasonable time to be ready respect the main plant engineering project that drive the corresponding initiatives; due to these reasons it is necessary to adopt Lean Simulation solutions; this is not a limitation, because, often, these *quick and dirty models* could be easily extended in terms of fidelity thanks to potential new improvements of computational efficiency and so they could be the starting point for further upgrades and developments. Currently the authors are extending these examples by developing new improved models for similar applications and to support different use of the simulators.

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