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Simulation of Power Plant Environmental Impacts within the Extended Marine Framework

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This paper proposes the use of Modelling and Simulation to analyse the different Environmental Impacts of Industrial Facilities with special attention to Power Plant located within the Extended Maritime Framework. The approach proposed is based on combining different simulation approaches to be able to reproduce the phenomena affecting this context in a comprehensive way. The simulation experimental results are dynamically presented and updated within a Synthetic Environment, based on a Serious Game, in order to be able to augment the virtual representation with additional information. It is proposed a case study related to a Power Plant including different Gas Turbines located in front the coast and the scenario include the evaluation of the emissions on the Atmosphere, Sea Water and Ground, the inclusions on these domains as well as their impact on the flora, fauna and social layers.

1. Introduction

The concept of sustainability is evolving along years therefore the related basic foundations are probably still valid: “the sustainability of ecosystems on which the global economy depends must be guaranteed and the economic partners must be satisfied that the basis of exchange is equitable” (Brundtland, 1987).
So to address this point it is fundamental to evaluate in comprehensive way the whole ecosystems including human installations (Liu et al., 2008). The complexity due to the explosive nature of the context, the long term effects of the decisions overpassing human horizons and the presence of multiple interactions and stochastic factors make it evident the necessity to move out of qualitative approaches and to adopt quantitative methods (Belcher et al., 2004). Obviously from this point of view Modelling and Simulation (M&S) result a strategic science to study these problems (Swart et al., 2004). Indeed, environmental impacts (EIs) of industrial processes, considering both pollution and acute major hazards, are very complex due to the fact that involve a myriad of factors and elements related to intrinsic chemical properties (Reverberi et al., 2016) and physical aspects (Fabiano et al., 2015) whose mutual interactions are still not very well known. Despite these facts, the possibility of model relationships between environmental impacts, industrial plant characteristics and operational modes could strongly improve the understanding of these phenomena; indeed, dependency and combined effects could be estimated by designing a hierarchical relationship model (Bruzzone et al., 2010). By utilizing a risk matrix and defining a target line of consequence-frequency combinations, it is possible to perform a cost-benefit assessment and answer the question how safe is safe enough, considering both acute risk and chronic environmental risk as well as environmental sustainability (Vairo et al., 2017). In the past, the authors developed these models focusing on Logistics as well as on Port Operations supporting the development of Green Solutions for these frameworks (Bruzzone et al., 2009). Recently, the evolution of policies on Greenhouse Gases had big impacts on industrial plants configuration, considering that several energy saving systems and policies, that are consolidated and already operational, have to be dismissed due to the change in tax policies (Zhang, 2016); this situation leads sometimes to strange solutions that are not really “energy saving”, but result effective in reducing taxes and fees (Burtraw et al., 2014).

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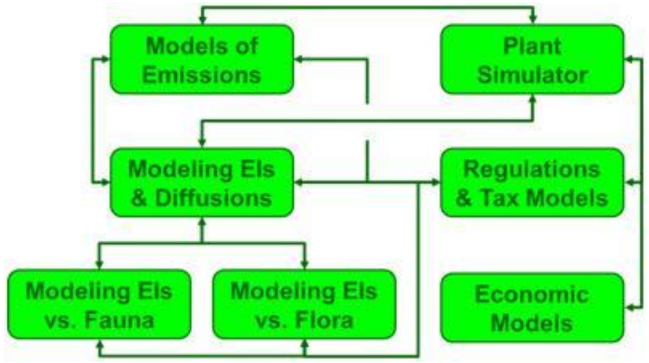

Figure 1: Models of the Power Plant EIs on the EMF

2. Simulation background

Due to these reasons, the authors are active in developing models to simulate the whole process and to address, in comprehensive way, the EIs over a complex framework; in this case it is proposed to study the Extended Maritime Framework (EMF) including air, underwater, sea surface, land and coast, etc (Bruzzone, 2014). In the past, the authors addressed this context in relation to operations with UxV (Unmanned multidomain Vehicles) that were integrated over a heterogeneous network (Bruzzone et al., 2016a); by the way these studies could be useful also in this case in order to develop future sensor networks with autonomous capabilities to investigate on symptoms and alerts: e.g. sending an Autonomous Underwater Vehicle, AUV, to check diffusion of emission at different depth in the sea. However, this paper proposes a case study related to a power plant to be simulated to estimate its EIs by adopting a combined and innovative modelling approach. The motivation to conduct this scientific study is to develop a comprehensive model of Environmental Impacts such as emissions in marine environment of a specific Power Plant with multiple Gas Turbine, therefore it is evident the possibility to adapt approach to many different cases of Industrial plants. Among the viable alternative systems to be evaluated, the model should allow to support a feasibility analysis related to an innovative process that redirects CO_2 emissions in Marine Environment. These simulators are addressing a wide spectrum of applications such as industrial plant engineering, emergency management, industrial processes, joint operations, homeland security and defence, logistics, innovative technologies, autonomous systems and decision support solutions. Indeed, Simulation Team is a non-profit organization involving individuals and organizations where different modules such as Green Log, MOSES and IDRASS (Bruzzone et al., 2013) have been implemented. The authors propose here to adopt the MS2G paradigm (Modeling, Interoperable Simulation and Serious Game) that allows to combine different models by adopting simulation interoperability standards and to guarantee the MMI (Main Machine Interface) through the Serious Game approach. Indeed, Serious Game, by immersive technologies and properly design representations, is able to improve usability and understanding for simulation users through a physical and emotional engagement.
In a different case study, the authors analysed a Power Plant Emission within a special CAVE (Cave Automatic Virtual Environment) developed ad hoc by Simulation Team in the frame of above mentioned MS2G solutions. This CAVE is named SPIDER (Simulation Practical Immersive Dynamic Environment for Reengineering) and is able to support distributed interactive simulation by combining continuous modelling of hazardous material spills and contaminations of air and soil with discrete event simulation about plant and autonomous asset behaviours (Bruzzone et al., 2016b).

3. Simulation models

The simulation to be developed in this research track adopts the HLA standards for interoperability (Kuhl et al., 1999); this approach enables the possibility to create a Federation of simulator that interoperate. In this way, it could be possible to federate different kind of models within the same context such as continuous simulation, discrete event simulation, combined simulation and system dynamics (Zacharewicz et al., 2005). Currently the authors are planning to combine different models addressing the different elements to be simulated as proposed in Figure 1. The proposed simulation uses different simulation techniques for reproducing plant operations, emissions, diffusions, EIs impact estimation and costs and regulation respect analysis; indeed, continuous simulation of emissions and diffusions in the marine environment are combined, for instance, with discrete event simulation of plant processes and system dynamics related. In order to complete successfully the Validation, Verification and Accreditation (VV&A) of the Simulator it is necessary to address different aspects and to develop the corresponding models as summarized in the following:

Plant Simulation:

The model of the plant and its operations is a crucial part of the simulation and should be based on a technical process (Ylén et al., 2005); by adopting MS2G paradigm it is possible to include a simplified plant meta-model during preliminary tests and experimentations.

This approach could allow to speed up the development and VV&A as well as to reduce the computational efforts for applying DOE (Design of Experiments) for optimization (Montgomery, 2008). On the opposite, further investigation on optimized configurations could be carried out substituting the meta-models with detailed plant simulator within the High-Level Architecture (HLA) Federation.

Modeling Different Power Plant Emissions :

The plant emissions should be identified and specific models should be developed to estimate their nature and flow rates (Bottenheim, 1982) and several year later (Lefebvre, 1998); for instance it should be possible to estimate the quantities of CO_2 and other components dispersed in regular configuration within the environment, modelling the relationships among emissions and different plant configurations; these models should consider the emission nature as well as the related characteristics under the different operational modes of the plant and along the years.

Modelling the EIs and their Diffusion in the EMF:

It is necessary to create diffusion models that should consider boundary conditions (e.g. temperature, wind, current, etc.) as well as release methods to estimate the diffusion of the emission in the Extended Maritime Framework (Moussiopoulos, 1990); these components should also take care of modelling the interaction of the EI within the sea water, terrain and Air in EMF, the model should estimate how much part of them dissolves in water and how much part still remains in it. An appropriate model should take into account the diffusivity phenomena, the interactions with the electrolytes contained in the environment (e.g. seawater) as well as the relevant equilibria of dissolved chemical elements.

The boundary conditions from this point of view represent crucial factors: for instance the effect of tides and currents affect the concentration profiles along the coast and in the deep sea and should be estimated by proper models. In similar way it is necessary to consider the medium and long terms of EI that will be dispersed in the different EMF domains according to thermodynamics of vapor-liquid equilibria.

Models of the EI impacts on EMF Flora

These models should cover the impacts of different EIs and emissions on the flora in terms of health status within the Extended Maritime Framework (Aleem, 1972) later (Suresh et al., 1993) and the most recently (Ou et al., 2016). For instance it should be necessary to develop models able to foresee the CO_2 concentration in water and its effects on algae population evolution, growth, reproduction as well as on the potential changes in their biological processes.

Models of the EI impacts on Marine Fauna

The adaptability of the EMF fauna to EI is another crucial component to be model and one of the most challenging in terms of environmental sustainability and eco-compatibility (Aleem, 1972) later (Suresh et al., 1993) and recently (Ou et al., 2016). For instance, a concentration map of emissions in water will be related to their biological effects on different living species to ensure the respect of the marine ecosystem. As for Marine Flora, these models should estimate the changes on growth, reproduction and biological processes concerning vertebrates and invertebrates and the impacts that these changes might have on other symbiotic species, humans included.

Economic Models

The economic models should deal with estimation of profits and costs related to different plant solutions and operational models, reproducing dynamically the market evolution and potential trends (Benz et al., 2009). Risk reduction strategies aiming at reducing frequency or mitigating the magnitude of the impact on the environment can be categorized as engineered active and passive; managerial/procedural; inherent (Palazzi et al., 2015). The estimation of fixed costs related to different plant configurations and/or systems and subsystems will be required to analyse the different solutions, therefore it is also possible to adopt a reverse engineering approach to estimate the threshold levels for feasibility of different solutions.

Modelling Policies, Taxations, Rules and Regulations

The Rules, Taxations and Regulations should be included in the model in order to estimate the taxes and fees related to different plant configurations and operational modes (Rafieisakhaei et al., 2016); in addition, this allow also to estimate the dynamical respect of threshold levels and policies along the plant life cycle; it is important to outline that these aspects deal with International and National regulations and the related models should be tailored for the different areas. The structure of the models should allow to change these conditions and parameters in order to reproduce different scenarios. These elements are today very important in order to understand the feasibility of plant refurbishments and changes according to economic advantages and compliances with existing laws and best practices. It is even fundamental to evaluate the effective advantage in terms of emission calculation in the environment and the regulations to be considered for the project feasibility.

4. Outline of the architecture model

The general architecture of the model includes different simulators to be federated together each one including some of the mentioned models; the relevant simulators are shortly introduced in the following:
VAED (Virtual Aided Engineering & Design) is a combined simulation (continuous and discrete event simulation) that reproduce the power plant principal and secondary systems as well as auxiliary plants and related processes, including thermodynamics and chemical reactions (Bruzzone et al., 1997). IDRASS (Immersive Disaster Relief and Autonomous System Simulation) is a MS2G (Modelling, Interoperable Simulation & Serious Game) environment combining discrete events and continuous simulation originally devoted to reproducing fall-out and spin off of hazardous material in industrial plants; this system could be tailored to reproduce dynamics of emissions and diffusion into the EMF during regular operations (Bruzzone et al., 2016b). GREENLOG PORT (Green Logistics for Ports) is a hybrid simulator allowing to consider the different EIs and to combine them based on a hierarchical structure (Bruzzone et al., 2010); the model has been developed for analysing Port Logistics and Processes, including ship emissions in air and sea and could be adapted to address this specific case study. MOSES (Modelling Sustainable Environments through Simulation) is a model based on system dynamics able to reproduce the impact of actions over an urban environment. This model could consider the EIs of different Power Plant configurations according to human, economic, environmental and social sustainability (Bruzzone et al., 2013). JESSI (Joint Environment for Serious Games, Simulation and Interoperability) is an interoperable simulation environment applied several time to the EMF (Bruzzone et al., 2016a); currently some kinds of marine fauna have been already successfully introduced (e.g. birds and sea mammals); due to these reason the models of marine flora and fauna could be introduced in this simulation; in addition it could be possible to reproduce and to estimate capabilities, costs and effectiveness on the use of AUV (Autonomous Underwater Vehicles) and UAV (Unmanned Aerial Vehicles) as solution to monitor and investigate the environmental impacts.
These simulators can interoperate and are integrated also with other solutions devoted to improving usability and VV&A through innovative MMI such as:
SPIDER (Simulation Practical Immersive Dynamic Environment for Reengineering) is an innovative Interactive CAVE (Cave Automatic Virtual Environment) developed by Simulation Team able to immerse multiple decision makers and/or scientists into a complex interoperable simulation. The basic configuration is compact (just 2m x 2m x 2.6m) and could be installed within a standard High Cube Container; SPIDER is fully compatible with any interoperable simulator and it has been already used to carried out experimentations with IDRASS and JESSI. Indeed, the SPIDER is interactive also through touch screen technology and it is fully immersive including sound and motion. ARTEM (Augmented Reality TErrain interoperable Module) is an interoperable HLA module designed to be integrated in a MS2G (Modelling, interoperable Simulation & Serious Game) systems. The results of the simulation are dynamically presented over smartphone and mobile devices providing them to the user in real-time and geo-referenced framework (Bruzzone et al., 2016b).

5. Applicative case-study

Preliminary results on experimental error estimations due to the stochastic factors related to CO_2 emissions are reported in Figure 2.

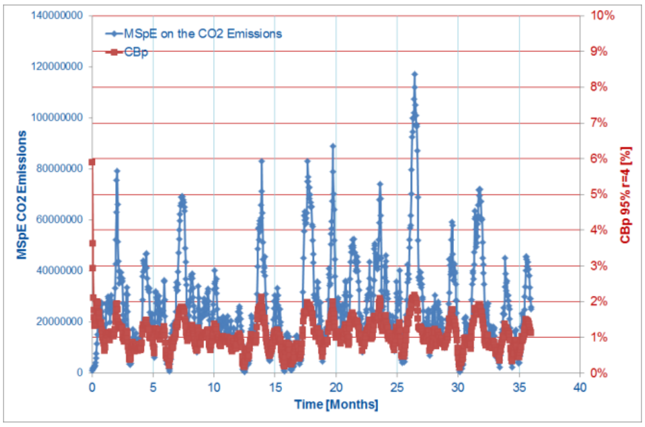

Figure 2: ANOVA on CO_2 emission for this case study.

The time evolution of the MSpE (Mean Square pure Error) is proposed as ANOVA (Analysis of Variance) in order to conduct the dynamic VV&A on the simulator (Bruzzone et al, 2016a); this approach allows to estimate its confidence bands expressed by the following relationship:

$$MSpE(t,r,j) = \frac{\sum_{i=1}^{r}\left[Y_{j,i}(t)-\bar{Y}_j(t)\right]^2}{r-1} \tag{1}$$

where MSpE(t,r,j) is the mean square pure error of j-th target function at t time with r replications, r is the number of replications obtained by running the simulation on same boundary conditions by changing only the random seeds, j is the j-th target function (in the proposed case emissions of CO_2) and $Y_{j,i}$ (t) is the value of the j-th target function on the i-th replication carried out by the simulator at t time.

Moreover, $\bar{Y}_j(t) = \frac{\sum_{i=1}^{r}\left[Y_{j,i}(t)\right]}{r}$ and $\bar{\bar{Y}}_j = \frac{\int_{t_s}^{t_e}\frac{\sum_{i=1}^{r}\left[Y_{j,i}(t)\right]}{r}dt}{t_e-t_s}$, where $\bar{Y}_j(t)$ is the average value of the j-th target function over r replications carried out by the simulator at t time, $\bar{\bar{Y}}_j$ is the average value of the j-th target function over r replications carried out by the simulator along the whole simulation and t_e,t_s are the ending and starting time of the simulation.

$$CB(t,j) = +2t_{\alpha,r-1}\sqrt{MSpE(t,r,j)} \tag{2}$$

$$CBp(t,j) = \begin{cases} \bar{Y}_j(t) <> 0 & \frac{CB(t,j)}{\bar{Y}_j(t)} \\ \bar{Y}_j(t) = 0 & \begin{cases} \bar{\bar{Y}}_j(t) <> 0 & \frac{CB(t,j)}{\bar{\bar{Y}}_j(t)} \\ \bar{\bar{Y}}_j(t) = 0 & 0 \end{cases} \end{cases} \tag{3}$$

CB(t,j) is the confidence band amplitude at t time for j-th target function and CBp(t,j) is the confidence band amplitude expressed in percentage respect average value of the j-th target function at t time.
The analysis has been conducted by using a simplified meta-model in VAED and confirms good level of experimental error and confidence band even after few simulated months of operations; obviously these results cannot be generalized depending on the scenario adopted for the operational use of the Power Plant, but the set of tests could be easily repeated to update the analysis. The authors are currently extending the experimental analysis to cover all different target functions related to the EI on different layers.

6. Conclusions

The proposed approach guarantees the possibility to investigate the impact of different aspects related to plant engineering solutions as well as to operational models; by this approach it becomes possible to understand clearly the effects of these elements on the multiple layers (e.g. air, water, flora, fauna, social, economic) of the Extended Maritime Framework. This research represents a first step towards the development of an experimentation on a more extended case study; until now the authors completed the identification of models and simulators to be used as well as the overall architecture. In the future, this modelling approach will be used to conduct experimentations for investigating the most effective solutions for CO_2 storage taking into account their environmental impacts on ground, sea and air factors and also considering their sustainability in terms of economic aspects and technical reliability.

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