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Integrative construct for Model-Based Human-System Integration: a case study

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Abstract:

A significant feature of critical systems such as power plants is their control by human operators. For that, they are placed at the field level where they perceive, process and provide the necessary information, which is partially digitalized. Another significant feature of the engineering of these systems is to focus mainly on technical requirements that are further checked by human factors and ergonomics specialists. Improving the co-specification process of these systems as a whole requires providing measurable requirements in order to bring together human and technical aspects of these systems. The resulting issue is to check the balance between the two types of specifications from an early project stage. In that way, we propose a system co-specification framework based on an integrative construct enabling to check the compliance of system requirements with automation and physiological requirements by co-execution of models. This framework is applied on a case-study in order to propose physical-physiological pre-requirements of a sound perception artefact by a field operator. These exploratory works aim to contribute to Model-Based Human-System Integration.

Keywords: Human-System Integration, Model Based Systems Engineering, Human-Machine Interaction, Requirements specification

1 INTRODUCTION

Many critical systems, such as power plants, are largely under human control at the field level even if automation mediates some tasks. It is due to the resilient nature of the human i.e. the capacity of operators to face non-nominal situations presented as the most important characteristic of safety oriented organizations (Hollnagel, 2006).

These critical systems with their enabling supports have to satisfy more and more requirements related to the dynamic nature of the physical process to control, the regulation rules imposed by safety even ethical and ecological standards and various control situations as the return to operational conditions after maintenance actions.

Thus, an important issue is the necessary evolution of current systems engineering (SE) frameworks (Ruault, Vanderhaegen, & Luzeaux, 2012) in order to early balance technical and ergonomic feasibilities to master human-machine task sharing in control operation (Millot, Debernard, & Vanderhaegen, 2011). That leads automation engineering to interoperate with Human-Centered Engineering (HCE) (Boy, 2011) within Systems Engineering (Pyster, et al., 2012) from ~~early~~ specification stages, in order to keep the system behaviour within an accepted domain of performances whatever the context of use.

This consensus to treat such socio-technical systems as engineering systems (Kroes, Franssen, van de Poel & Ottens, 2006) requires to unify (SE) and (HCE) in order to meet Human System Integration (HSI) (Boy, 2013), to which these works could contribute.

Section 2 presents the studied user-automation sound-perception interaction within the real context of our domain of interest (Devic, & Morilhat, 2013). Section 3 focuses on a functional construct of this interaction as integrative driver of our requirements co-specification process. Section 4 presents the framework of the integrative physiology in order to model the studied interaction. Section 5 details a particular scenario leading to check the compliance of a co-specification of this interaction with some physical-physiological pre-requirements between the domains of systems and ergonomics engineering. We present in section 6 our ongoing works and future developments in order to improve the readiness level of these exploratory works for meeting real operational HSI issues.

2 USER-AUTOMATION INTERACTION CASE-STUDY

Some critical power plants, especially nuclear ones, exhibit complex control interactions where operators, i.e control room operators and field operators (FO), interoperate together to perform documented procedures by the means of partially automated devices. The goal is to master the dynamics of a physical and partly 'natural' process by providing the information representation of the plant state to control room operators in order to properly make decisions during normal as well abnormal operations. This representation is partially achieved by the instrumentation and information control systems. However, for business and technical requirements, it is not possible to instrument all components at plant level and about 80 % of the information reported in the control room is not automated but is provided by local operators (FO, chemists, maintenance operator…). For example, the number of manual valves in a power plant is estimated at 20000 units while motorized and pneumatic valves represent only 1350 units of the overall equipment. That highlights the fundamental role of FOs in close control loop with the process as addressed by (Galara, 2006) to specify the interactions I_{AU} between the automation artefact[1] and the user, to I_{AP} between the automation artefact and the process, and to I_{UP} between the user and the process to control (Fig.1).

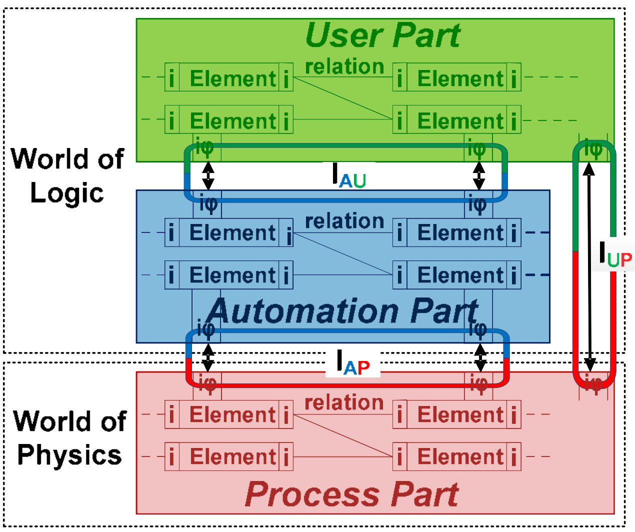

Fig.1: Interactions between process, user and automation parts during process control

[1] According to (Kroes, Franssen, van de Poel & Ottens, 2006), Artefact to be designed is an object with a specific technical structure embedded in a use plan

Artefact-Process Interaction I_{AP}

I_{AP} is supported by instrumentation and information control systems aiming "to measure thousands of variables and to process the data to activate pumps, valves, motors, and other electromechanical equipment that control the plant" as addressed by (Tsvetkov, 2011). Furthermore, they contribute to form a partially information representation (*in the world of logic*) of the process part (*in the world of physics*) but restricted to what can be perceived by instrumentation with the remaining problem of its location.

User-Process Interaction I_{UP}

Missing information to form a more complete representation of the process to control is collected by FOs. Moreover, FOs work closely to the physical system to actuate a lot of devices which cannot be instrumented (Dobre, Morel, Pétin, & Bajic, 2008). This I_{UP} stands on human senses (viewing, hearing, smelling, touching) restricted to the external perception of some manifestations of the process, for example the shape, the colour, the perceptible temperature and vibration, and the direct manipulation of valves, pumps,…(Galara, 2006). By so doing, FOs perceive and interpret many physical phenomena and provide the necessary amount of information which consequently is not digitalized. In others words, the supervisory tasks could be automated but not the FOs activities, so that it is of importance to check that FOs perceive right to right acting, as studied in another maintenance context (Lieber, 2013). So, mastering I_{UP} is vital to face a lot of non-nominal situations which are not under the artefact control.

Artefact-User Interaction I_{AU}

From the past when "control room operators interact with technical parts throughout a large control panel, taking reading from gauges and adjusting knobs and levers, many of today's control rooms have been upgraded, replaced or augmented with visual display units" (Carvalho, dos Santos, Gomes, Borges, & Guerlain, 2008). I_{AU} provides the interface between operators and the related automated/digitalized devices at plant level, including for warning purposes. Nevertheless, the use of such enabling information technology to increase field operators information capabilities remains under debate waiting the assessment of their HSI readiness level.

This overall description of the real context of our domain of interest is compliant with the AUTOS framework (Boy, 2011), even if some definitions such as artefact remains open to debate between the HSI communities. Our case-study focus on improving the specification of the interaction I_{AU} of a field operator in the particular situation of maintaining operational an auxiliary feedwater subsystem (AFW) of a power plant when a sound warning occurs (Fig. 2).

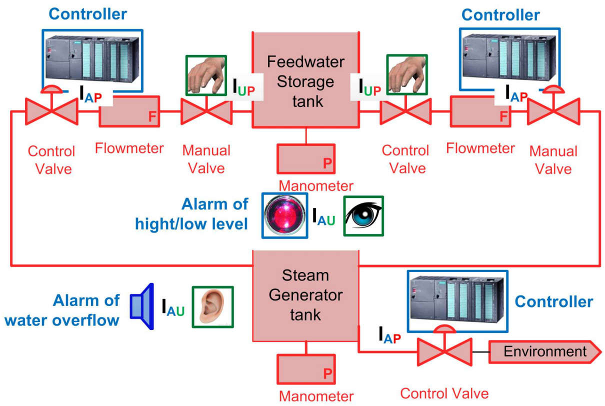

Fig.2. Some I_{AP}, I_{AU} and I_{UP} interactions of our CISPI[2] AFW-like process to control

3 MODEL-BASED CO-SPECIFICATION FRAMEWORK OF THE STUDIED INTERACTION

A recent study for SE industrial issues (Fanmuy, Fraga, & Llorens, 2012) highlights the use of models beyond current practical guidelines in requirements specification to improve the engineering performance of a project.

We pointed out in previous works (Lieber, 2013) that checking by execution of models the compliance of system technical requirements with ergonomic requirements at an early stage of co-specification could contribute to improve the HSI performance. So, we explored the measurability of physical-physiological requirements to model an interaction of visual perception such as I_{AU} in a real maintenance situation. These works suggested that the overall system specification process is led by iterative relationships of description and prescription of requirements between the operational domain and the SE domain and between the SE domain and two main specialist domains of ergonomics and automation engineering. The SE domain is responsible to orchestrate these causal specification relationships between problem-spaces (PS) in charge of integrating sub-systems and solution-spaces (SS) in charge of designing sub-systems for satisfying the originating operational requirements of the desired system as a whole.

In order to improve a lean management of the overall model-centric workflow, our on-going works distribute this co-specification process around a bus (Fig.3). A main interest is that engineers from various domains can use their own tools, methods, technics in order to interoperate by the mean of a common language, such as the de-facto standardized SysML[3] in our case-study The checking of specifications with requirements is performed by co-execution of models in order to replace current technics of code generation and integration which depend on interoperability levels between tools.

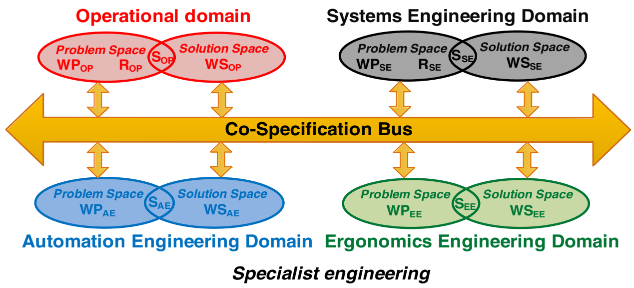

Fig. 3. SE-centric distributed co-specification process

In the same way that the 'problem frame approach' of (Jackson, 1997) in software engineering but at the scale of an overall SE process and beyond for HSI, we suggest that the driver of this co-specification process is an early quest for knowledge as design property from any specialist to the system engineer. As revisited by (Jin, 2006), we argued that this quest for knowledge explains the role of any concurrent domain knowledge in the overall co-specification iterative process and where these knowledge must be used.

Let's consider some iterations of the co-specification of our studied interaction I_{AU}. The SE solution space (WS_{SE}) is responsible for the system specification S_{SE} to satisfy requirements R_{OP} from the operational problem space (WP_{OP}) according to the entailment:

$$WP_{OP}, S_{SE} \vdash R_{OP} \tag{1}$$

«Operational» Normative_Requirement_Abnormal_Conditions
ID = R_OP
The field operator shall be alerted if an abnormal conditions in plant status is detected
Sink_From: Operational_Enginnering_PS **Source _To:** Systems_Engineering_SS

By keeping in mind HSI issues, a further stage of our iterative co-specification consists for the quest for knowledge from the ergonomics solution space (WS_{EE}) which is responsible for sub-system specification S_{EE} to satisfy requirements R_{SE} from the SE problem space (WP_{SE}) according to entailment:

$$WP_{SE}, S_{EE} \vdash R_{SE} \tag{2}$$

[2] CISPI reflects on a lab-platform some critical features of a real AFW system http://safetech.cran.uhp-nancy.fr/

[3] OMG Systems Modeling Language (OMG SysML) http://www.omgsysml.org/

«Problem» Human_Sound_Perception
ID = R_SE
Human shall perceive an audible alarm in a noisy environment.
Sink_From: Systems_Engineering_PS **Source _To:** Technical_Enginnering_SS & Ergonomics_Engineering_SS

The same rationale is applied for the quest for knowledge from the automation solution space (WS_{AE}) for sub-system specification $S_{AE.}$ The balancing checking of these specialist specifications with R_{SE} is performed by co-simulation of models. Thus, by proposing such a distributed iterative co-specification process, we suggest a possible collaborative work, through the SE problem space (WP_{SE}), between specialists of ergonomics (WS_{EE}) and automation (WS_{AE}) domains to obtain measurable HSI specifications (S_{EE} and S_{AE}) that satisfy originating operational requirements R_{OP}.

The overall specification effort implies to well define the context where the system under specification will behave and interact with the related entities of this context before to derive its internal structure.

A special attention must be paid to model the external manifestations that the required system has to stand up with its environment entities. The set of phenomena contained in an interaction can change dynamically its behaviour, so that it is important to make explicitly an entity from the interaction (Ducroq, 1996). Nevertheless, even formal methods depend on cognitive abilities and technical capabilities of the modeller for structuring any overall domain knowledge. So, we suggest using a pattern (Fig. 4) in order to turn the interaction specification into a substantive construct.

The goal is to well define the necessary physical properties of the source automation part (Alarm artefact) which are propagated through the studied interaction to the sink user part (Field Operator). We argue that it is an early pre-requirement of the interaction, even if not sufficient from the overall human factors. Interactions are now entities embedding some domain knowledge (WS_{EE}) to be structurally and behaviourally specified. Next section focuses on the physical-physiological nature of the studied sound-perception interaction (I_{AU}). Section 5 illustrates the iterative use of this construct to check the compliance of the studied interaction specification (S_{EE}) with the problem statement (R_{SE}).

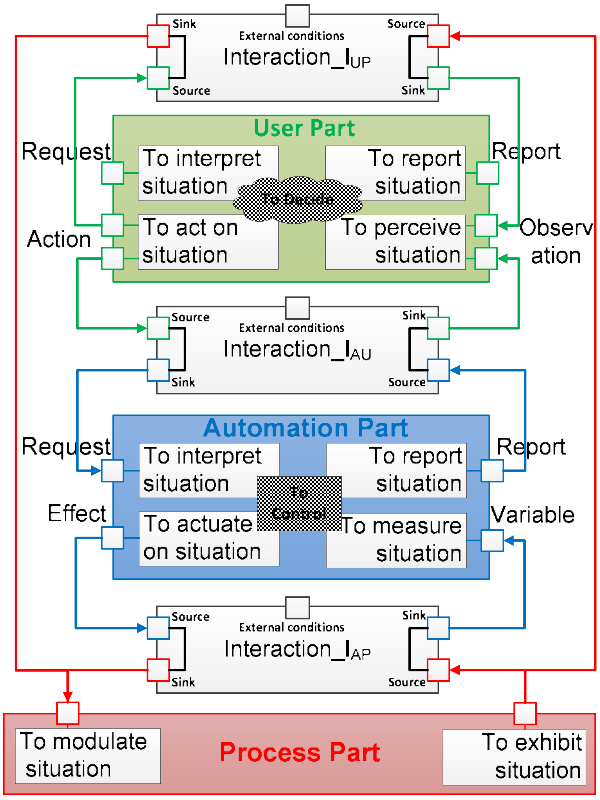

Fig.4. Interaction and control constructs of our control pattern related to Fig.2

4 INTEGRATIVE PHYSIOLOGY FRAMEWORK TO MODEL THE STUDIED INTERACTION

Ergonomics knowledge about the nature of the sound perception interaction I_{AU} focuses on works related to the understanding of the human perception process in order to specify measurable requirements. This integrative physiology framework is mainly based on the works of perception and action physiology by (Berthoz, 2012) and more generally on works dealing with Mathematical Theory of Integrative Physiology (MTIP) by (Chauvet, 1993).

Our rationale of selecting the MTIP is linked to the functional representation of a living system which related framework supports a physiological process-based modeling, like others technical process-based modeling. These physiological processes are hierarchically organized within space and time scales and stimulated by a set of functional interactions such I_{AU} that spread over structural discontinuities (Fig. 6). Such discontinuities modify the nature of I_{AU} that is of importance when transmitting a physical flow from a source entity to a sink physiological entity. We argue that I_{AU} is a physical-physiological interaction, meaning that a physical flow is propagated from a physical environment to a physiological one before to be transmuted into a biological flow.

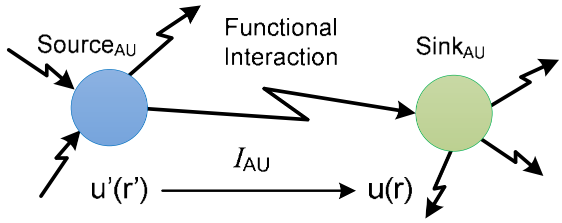

Fig.6. Perceptive Functional Interaction I_{AU} between a source (*sound signal*) located in r' and a sink (*human organic unit*) located in r.

From our precedent works on the visual perception (Lieber, 2013), we revisit the nature of the physical-physiological interaction modeling in terms of power in order to unify HSI modeling with current technical modeling. More generally, and whatever the nature of sensory perception, a transduction mechanism leads to converse the physical-physiological interaction as an electrical current, that propagates through the cerebral tissue (Purves et al., 2011). The electrical dynamics can be treated in terms of transported power through circuits (Emanuel, 2010) and therefore some functional interactions could be regarded as a transported power.

Depending on the available biological data, we focus to identify the right physiological entity (Sink) to specify the right physical flow required by the technical entity (Source) in order to stimulate the cognition. Fig.5 depicts the physiological point of view of our case study.

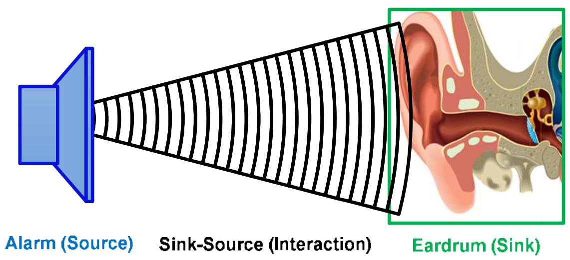

Fig.5: A technical source (*Alarm*) located in the physical environment interacts with a physiological sink (*eardrum)* located in the biological environment.

5 CO-SPECIFICATION OF THE STUDIED PHYSICAL-PHYSIOLOGICAL INTERACTION

The modeling of the studied physical-physiological interaction is constraint by our functional construct (Fig.4) into three SysML blocks related to *the Artifact-Source, the Interaction Sink-Source and the User-Sink*. According to entailment (2), each block provides a part of the specification S_{EE} from which the compliance with the system requirement R_{SE} is checked by execution of models.

Sound User Block

The human ear can detect sounds in a frequency range from about 16 Hz to 20 kHz (between the infra and ultra – sounds) within a frequency-dependent power (usually expressed in log units known as decibels, abbreviated dB) and represented by a specific human hearing area (Human Hearing Ranges) (Goldstein, 2009). The pressure wave quantity received by the eardrum through the external auditory meatus is transmitted to the inner ear before to be transmuted into an amount of electrical power.

«Functional» Sound User Sink
ID = U1
The pressure wave received by the External auditory meatus shall satisfy the human hearing ranges (frequency dependent threshold of hearing shaped by an audibility curve)
Sink_From: Ergonomics_Engineering_SS **Source _To:** Systems_Enginnering_PS

The effective auditory perception (at the sink level) needs also a sufficient duration of hearing according to the measurable requirement U_{11} (Müller, & Möser, 2013). (Part: *Hearing_System_Sink:Human_To_Perceive_Situation* in Fig.8).

«Functional» Sound Duration Sink
ID = U11
Duration of the heard sound shall be at least equal to period that is the inverse of the frequency (for a pure sound and expressed in second)
Sink_From: Ergonomics_Engineering_SS **Source _To:** Systems_Enginnering_PS

And to facilitate the hearing of the sound source location, the binaural system (having or relating to two ears) should satisfy the geometrical (or space) measurable requirement U_{12} (Warren, 2008).

«Functional» Sound Anthropometric Alignement Sink
ID = U12
The anthropometric axes shall be aligned in order to satisfy the binaural system in the localization of the sound source
Sink_From: Ergonomics_Engineering_SS **Source _To:** Systems_Enginnering_PS

Note that this last requirement is source of an interoperation with another ergonomics sub-specialist within the HCE domain acting as architect for human factors (Lieber, 2013).

Sound Interaction Block

For sound perception, the interaction is a pressure wave (wave behavior of the interaction). Its intensity can be evaluated by the decimal logarithm of the ratio of two pressures, the first one is the RMS (Root Mean Square) sound pressure or effective sound pressure and the second one is the standard reference sound pressure in air (equal to 20 µPa). The square of the pressure is proportional to the sound power measured in W.m^{-2} (Müller, & Möser, 2013). (Part: *Sink_Source:Interaction_IAU* in Fig.7)

Some of its physical proprieties as velocity could be modulated, or altered by some environmental characteristics, as temperature or humidity (Müller, & Möser, 2013). Moreover, as human operators are immersed in a noisy environment within the most of industrial sites such as critical power plant, this background noise or ambient noise could be regarded as a sound interaction. This noisy pollution can go in competition with other intelligible sound interactions (as an audible alarm) and therefore can mask them. A new measurable requirement UA_1 can be directly specified from French security standard (NFS 32011).

«Functional» Sound Interaction
ID = UA1
the sound source shall generate sound waves with a sound intensity (dB) at least a sound intensity greater than 10 dB with respect to the intensity (dB) of the background noise
Sink_From: Ergonomics_Engineering_SS **Source _To:** Systems_Enginnering_PS

Sound Artefact Block

The required quantity of 'pressure waves' depends directly of the propagated one from the sound source (alarm for example) according to the measurable requirement A_1 (Müller, & Möser, 2012) (Part: *Alarm_Source:Technical_To_Actuate_Situation* in Fig.7).

«Functional» Sound Frequency Source
ID = A1
The sound source shall generate sound waves within a frequency w between 16Hz and 20kHz and a sufficient frequency-dependent power E.
Sink_From: Ergonomics_Engineering_SS **Source _To:** Systems_Enginnering_PS

The interaction construct allows ergonomics engineer to design and to structure its specification S_{EE} as a set of requirements related to each block: S_{EE} = *{U1, U11, U12, UA1, A1}*. This specification S_{EE} is structurally represented with the system engineer by a SysML Internal Block Diagram (IBD) (Fig.7). Note that an ergonomics solution space doesn't have the knowledge to specify the bloc "*Alarm_Source*". This task will be performed by automation engineer according to system engineering requirement (R_{SE}) but also ergonomics engineering specification (S_{EE}) which prescribes the necessary physical requirements to perceive an audible alarm.

Checking specification S_{EE}

In order to verify and to validate the S_{EE} specification, the static resulting SysML block must be dynamically executable by simulation (Fig. 7). SysML diagrams (IBM Rhapsody®) and functional block diagrams (Matlab/Simulink®) which implements the physic-physiological behaviors can be co-executed.

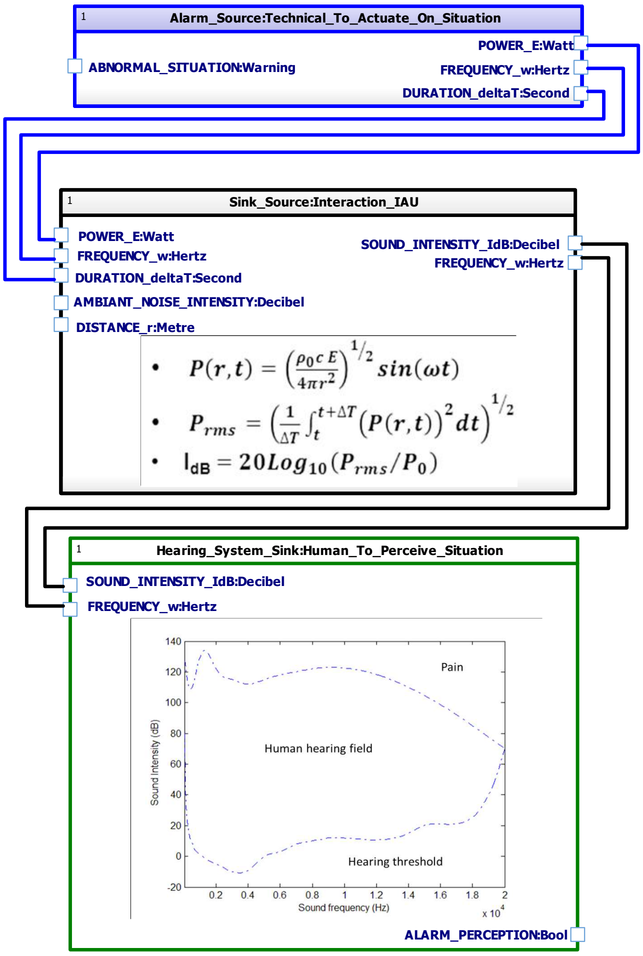

Fig.7: Specification S_{EE} of audible alarm (Source) perception by a human (Sink) represented in SysML IBD

The behavior of the *User-Sink Block* is simulated with current available date in order to define the area of right perception of the hearing field (Fig. 8).

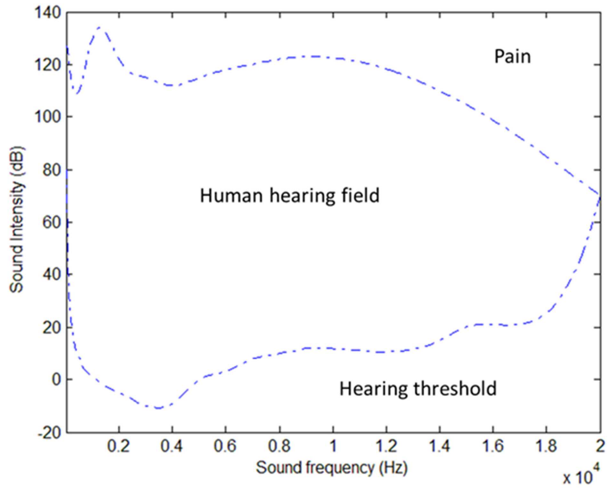

Fig.8. Current human hearing range depending on the frequency and the intensity of the sound wave

Fig.9 depicts a particular test case among others to check the satisfaction of entailment (2). For example, the emitted sound (1W, 20Hz) is well perceived up to a distance of 40 meters on condition to respect the UA_1 requirement (background noise)

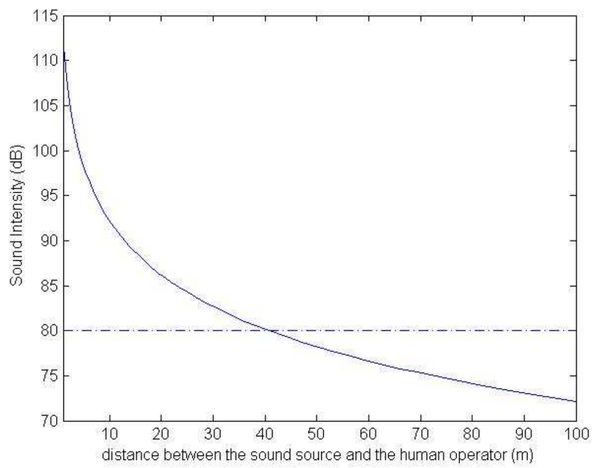

Fig.9. Simulated checking of the co-specification S_{EE} for a particular requirement R_{SE}

6 CONCLUSION AND FUTURE WORKS

We propose an integrative construct in order to orchestrate the iterative co-specification of an *Artefact-User Interaction* between a system engineering domain and two main ergonomics (physiology) and technical (automation) specialist domains. These works are based on the physical-physiological modeling of this type of interactions in order to check its compliance with a system specification by co-execution of models. Although this approach depends on the available biological data, others related environments are providing physiological models[4] and can be integrated within our co-simulation environment.

Others works within the same co-specification framework are focusing on the interpretation of the sensory functional interactions I_{AU} and I_{UP} in terms of power and in terms of the main senses (viewing, hearing, smelling, touching) involved in a real context of critical power plant control. We are also exploring to enlarge the definition of the *User-Sink Block* behaviour by others modeling techniques such as design of experiments in order to better check the compliance of the interactions specification with operational requirements.

Proof of concept of these exploratory works is actually performed on the CISPI lab-platform environment and must be developed to meet higher levels of technology readiness to an operational environment. These increasing levels of maturity imply to refine the external conditions which modify the behaviour of sensory interactions.

These works, as well as our co-specification and co-simulation environment with the use of SysML could contribute to meet HSI issues

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