Neuroergonomics and Cognitive Engineering, Vol. 102, 2023, 28–38
https://doi.org/10.54941/ahfe1003002

Probabilistic Analytical Modelling in Some Critical Human-in-the Loop (HITL) Problems, Its Role, Significance, Attributes and Challenges

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ABSTRACT

The probabilistic predictive modelling (PPM) concept in ergonomics engineering (EE), addressed in this analysis, is based on a physically meaningful modelling followed by a highly focused and highly cost-effective failure-oriented experimentations (FOEs) geared to the chosen predictive model(s). The concept enables quantifying, on the probabilistic basis, the outcome of a particular human-in-the-loop (HITL) effort and making the never zero probability the human failure low enough and adequate for a particular system and application. Analytical ("mathematical") modelling is employed in this analysis. In the authors' opinion, such modelling should always complement computer simulations: these two major modelling tools are based on different assumptions and employ different calculation techniques, and if the results obtained using these tools are in agreement, then there is a good reason to believe that the obtained data are accurate and trustworthy. The recently developed Systemic Structural Activity Theory (SSAT) is another possible way to improve the state-of-the-art in the EE. By making the design flow apparent and effective this theory enables improving efficiency and productivity of the human performance and saves resources at the early stages of the design. In this brief review the recent publications of the authors on the PPM and the SSAT are addressed.

Keywords: Ergonomics engineering (EE), Figure-of-merit (FOM), Human factor (HF), Human factor engineering (HFE), Human non-failure (HNF), Human-capacity-factor (HCF), Human-in-the-loop (HITL), Human-system integration (HSI), Mental workload (MWL), Probabilistic predictive modelling (PPM), Sensitivity analysis (SA), systemic structural activity theory (SSAT)

INTRODUCTION: MOTIVATION AND BACKGROUND

There is a significant potential for improvements in EE tasks and problems through better understanding, through effective PPM, the role that various uncertainties play in the planner's and operator's worlds of work, when never-perfect human, never failure-free equipment and instrumentation, never 100%-predictable response of the object of control (such as, e.g., a robot, a car, a railroad train, a marine vehicle, or an air- and space-craft) and uncertain-and-harsh environments contribute jointly to the outcome of a critical HITL undertaking. In effect, the difference between a reliable human, system, object, product or a mission and an unreliable one is "merely" the difference in the levels of their never-zero probabilities of failure. By developing and employing measurable and quantifiable ways of assessing the roles and significances of various critical uncertainties and treating a HITL as a part, often the most crucial part, of a complex human-instrumentation-object-of-control system and its interfaces one could assess and possibly assure the success and safety of an EE undertaking of importance, thereby improving dramatically the state-of-the-art in the EE field. The traditional, HF oriented, EE approaches are typically based on experimentations followed by statistical analyses. The probabilistic approach, based, first of all, on the PPM, facilitates, by providing prior quantitative assessments, a much better understanding of the needs, attributes, challenges and results of integration human capabilities (cognitive/mental, physical, sensory, team dynamics, etc.) with a particular system. The ultimate goal of the HSI is, as is known, to optimize total system performance, including costs. Situations, in which the performance of the HITL and of the equipment/instrumentation contribute jointly to the outcome of a critical undertaking were addressed by Cosmides and Tooby, 1996; Gilovich, Griffin and Kahneman, 2002; Kahneman and Frederick, 2002, and, recently, by Suhir, Scataglini, and Paul, 2020; Suhir, Paul and Kaindl, 2020; Suhir and Paul, 2021; Suhir, 2021d; Suhir, Karwowski and Bedny, 2021. The primary HFE concern is the need for an in-depth understanding of the ergonomics and physics of possible failure, as well as the effective integration of the HF with the system's attributes. This need drove hundreds of suggestions on how to improve possible HITL designs and operations. It has been recognized, particularly, that no essential progress is possible, if the considered measures and their effects are not quantified. This is true, generally speaking, for any engineering undertaking, not only those in the HFE domain (see, e.g., Watson, 2000; Paley, 2005; Chung, Rabe-Hesketh, Dorie, Gelman, and Liu, 2013; Vukovic and Lesaux, 2013; Suhir, 2015, 2017b, 2018a, b, 2019g, 2020b, c, e, 2021a, b, c, 2022a; Weixler, Sommerhoff and Ufer, 2019; Niss and Blum, 2020). Efforts were concentrated on maximizing the overall human-system performance through improvements in human MWL, but considering also the level of the HCF (see, e.g., Suhir, 2019f): it is the quantified HCF-to-MWL ratio, deterministic or random, that could be viewed as a suitable quantified characteristic of the ease of maintenance, personnel safety, cost effectiveness and prevention of injuries and fatalities in an EE system of importance. This paper addresses, first of all, the significance, role, attributes and challenges in the probabilistic, "prior", analytical ("mathematical") modelling (see, e.g., Kahneman and Tversky, 1972, 1979; Tversky and Kahneman, 1974, 1983; Kahneman, Slovic and Tversky, 1982; Gigerenzer, Swijtink, Poster, Daston, Beatty and Krueger, 1989; Reeves and Lockhart, 1993; Liu, Lo and Wu, 1996; Fischbein and Schnarch,1997; Suhir, 1997a,b, 2014a, 2016, 2017a; Macchi, 2000; Budgett, Pfankuch and Franklin, 2016; Reani, Davies, Peek and Jay, 2019) in some critical HITL tasks and problems, rather than statistical, "posterior", evaluations (see, e.g. Hoffrage, Lindsey, Hertwig and Gigerenzer, 2000; Rastfeld, 2004; Brase, Fiddick, and Harris, 2006; Brase, 2014; Buehner and Ziegler, 2017; Bruckmaier, Binder, Krauss and Kufner, 2019), including the s.c. Bayesian statistics (see, e.g., Chapman and Liu, 2009 and Suhir, 2014c). Here are several areas, in which PPD has been employed:1) probabilistic modelling in engineering and applied science in general (see, e.g., Augusti, Baratta and Cascati, 1984; Hatchison, 1985; Suhir, 1974, 1997a,b; 2010;2019a,b; Bolotin, 1985); 2)medical applications (see, e.g., Eddy, 1982; Galestic, Gigerenzer and Straubinger, 2009; Garcia-Retamero and Hoffrage, 2013; Pighin, Gonzales, Salvadori and Girotto, 2016; Operskalski and Barbey, 2016; Suhir and Yi, 2017; McDowell, Galesic and Gigerenzer, 2018; Suhir, 2022a; Suhir and Bedny, 2022, 2022a); 3)aerospace applications (see, e.g., Suhir, 2009b, 2011, 2012a,b, 2019d,e, 2021e; Suhir and Mogford, 2011; Salotti and Suhir, 2014; Suhir, Bey, Lini, Salotti, Hourier, Claverie, 2014); 4) automated driving applications (see, e.g., Suhir and Paul, 2020, 2022; Suhir, Scataglini and Paul, 2021; Suhir, 2022b); 5)application of the multi-parametric Boltzmann-Arrgenius-Zhurkov (BAZ) constitutive model (Suhir and Kang, 2013; Suhir 2020a); 6) role of trust (Suhir, 2019c; Suhir, Scataglini and Paul, 2021).

EXSAMPLES

Medical/Aerospace Application

Let us address, as a suitable example of medical application of the PPM, probabilistic HSI in aerospace engineering, or, specifically, navigator's (aircraft pilot's or astronaut's or even a train machinist or a car driver) performance vs. his/hers HCF, considering his/her state-of-health (SoH). The following double-exponential-probability distribution function (DEPDF) for the probability of HnF, when performing in a mission of importance, or when encountering an off-normal situation, is suggested (see details in Suhir, 2021e):

$$P^h(F, F, S_*) = P_0 \exp\left[\left(1 - \gamma_S S_* t - \frac{G^2}{G_0^2}\right)\exp\left(1 - \gamma_T T_* - \frac{F^2}{F_0^2}\right)\right].$$

This function enables evaluating the impact of three major factors, the MWL G the HCF F, and the progressed time t (possibly affecting the navigator's performance, such as, e.g., the likelihood to make a mistake, and sometimes even his/hers health), on the probability of the HnF. Here P_0 is the initial probability ($t = 0$) and at a normal (sufficiently low) level of the MWL ($G = G_0$), S_* is the threshold (acceptable level) of the (supposedly continuously monitored/measured, cumulative, effective, indicative, and possibly even multi-parametric) human health ("medical") characteristic, such as, e.g., body temperature, arterial blood pressure, oxyhaemo-metric determination of the level of saturation of blood haemoglobin with oxygen, electrocardiogram measurements, pulse frequency and fullness, frequency of respiration, measurement of skin resistance that reflects skin covering with sweat, etc. etc. (since the time t and the threshold S_* enter the above governing expression as a product $S_* t$ each of these parameters has a similar cumulative impact on the sought probability); γ_S is the sensitivity factor for the symptom S_*; $G \geq G_0$ is the actual (elevated, off-normal, extraordinary, possibly even time-dependent) MWL; G_0 is the MWL at ordinary (normal) operation conditions; T_* is the mean time to error/failure (MTTF); γ_T is the sensitivity factor for this time; $F \geq F_0$ is the actual (could be off-normal) HCF exhibited or required in a particular condition/situation of importance; F_0 is the most likely (normal, specified, ordinary) HCF. There is a certain overlap between the levels of the HCF F and the MTTF T_* value, which has also to do with the human quality and performance. The difference is that T_* is a short-term characteristic of the navigator's performance that might be affected, first of all, by his/hers personality and vulnerability to various influences, while the HCF is a long-term characteristic of the HITL, such as his/hers age, education, experience, ability to think and act independently and under pressure, and, if necessary, as a team player, etc. etc. The MTTF T_* might be determined for the given individual by using a highly focused failure-oriented-accelerated-testing (FOAT) on a flight simulator (Suhir, 2019b), whatever the appropriate definition of failure in such testing might be, while the HCF F, which should also be quantified, cannot obviously be evaluated experimentally and should be quantified using a specially designed methodology. It is noteworthy also that while the P_0 value is defined as the probability of the HnF at a very low MWL level G, it could be determined and evaluated also as the probability of the HnFfor a hypothetical situation, when the HCF F is extraordinarily high, i.e., for a navigator who is exceptionally highly qualified (like, say, Captain "Sully" in the famous "miracle-on-the-Hudson" event (Suhir 2012a), while the MWL G is still finite, and so is the operation time t. The suggested governing DEPDF function has a nice symmetric form. Indeed, it reflects the roles of the "objective", "external", MWL+SoH impact $E = \left(1 - \gamma_S S_* t - \frac{G^2}{G_0^2}\right)$, as well as of the "subjective", "internal", HCF+HE impacts $+ = \left(1 - \gamma_T T_* - \frac{F^2}{F_0^2}\right)$.

Here is the rationale below the structures of these expressions. The level of the MWL could be affected by the human's state-of-health (SoH): the navigator might experience a higher MWL, which is not only different for different individuals, but might be quite different for the same individual, depending on his/hers current, short-term, SoH, while his/hers HCF, although could also be influenced by the state of his/hers SoH, affects the probability of the HnF indirectly. In our approach the impact of the SoH could be measured/quantified by the navigator's mean-time-to-error (MTTE) T_*, since the human error (HE) is, in effect, a failure in his/hers otherwise error-free performance process, is it not? When the human's qualification is high, the likelihood of an error is most likely low, regardless of how harsh the external conditions are. Thus, in our model the "external" factor E=MWL+SoHis a more or less short-term characteristic of the human performance, while the "internal" factor I=HCF+HE is a more permanent, a long-term characteristic of the navigator's HCF. It is also noteworthy that the human's mind (reflected by his/hers MWL) and his/her body's SoH are closely linked, that such link is different for different individuals, and that is at present far from being well defined and more or less clearly understood. The suggested formalism is, of course, just a possible and a highly tentative way to account for such a link. Difficulties may arise in some particular occasions when the MWL and the SoH factors overlap. It is anticipated therefore that the MWL impact in the suggested formalism considers, to an extent possible, various more or less most important influences other than the direct SoH related one.

HCF, unlike MWL, is, as is known, a relatively new notion in EE (Suhir, 2019g). HCF plays with respect to the MWL approximately the same role as strength/capacity plays with respect to stress/demand in structural analysis and in some economics problems. HCF includes, but might not be limited to, the following major qualities that would enable a professional human to successfully cope with an elevated off-normal MWL: age; fitness; health; personality type; psychological suitability for a particular task; professional experience and qualifications; education, both special and general; relevant capabilities and skills; level, quality and timeliness of training; performance sustainability (consistency, predictability); independent thinking and independent acting, when necessary; ability to concentrate; awareness and ability to anticipate; ability to withstand fatigue; self-control and ability to act in cold blood in hazardous and even life threatening situations; mature (realistic) thinking; ability to operate effectively under pressure, and particularly under time pressure; leadership ability; ability to operate effectively, when necessary, in a tireless fashion, for a long period of time (tolerance to stress); ability to act effectively under time pressure and make well substantiated decisions in a short period of time and in an uncertain environmental conditions; team-player attitude, when necessary; swiftness in reaction, when necessary; adequate trust (in humans, technologies, equipment); ability to maintain the optimal level of physiological arousal. These and other qualities are certainly of different importance in different human-in-the-loop (HITL) situations. It is clear also that different individuals possess these qualities in different degrees. Long-term HCF could be time-dependent.

To come up with suitable figures-of-merit (FoM) for the HCF, one could rank, similarly to the MWL estimates, the above and perhaps other qualities on the scale from, say, one to ten, and calculate the average FoM for each individual and particular task. Clearly, MWL and HCF measurements should use the same units, which could be particularly non-dimensional. Special psychological tests might be necessary to develop and conduct to establish the level of these qualities for the individuals of significance. The importance of considering the relative levels of the MWL and the HCF in human-in-the-loop problems has been addressed and discussed in several earlier publications of the first author and is beyond the scope of this analysis.

In connection with the taken approach it is noteworthy also that not every model needs prior or even posterior experimental validation. In the author's view, the structure of our governing model does not. Just the opposite: this model should be used as the basis of the FOAT to establish the MWL, HCF, and the levels of HE through the corresponding observed and recorded MTTF and his/hers SoH at normal operation conditions and for a navigator with regular skills and of ordinary capacity. These experiments could be conducted, e.g., on different flight simulators and on the basis of specially developed testing methodologies. Being a probabilistic, not a statistical model, the above equation should be used to obtain, interpret and to accumulate relevant statistical information. Starting with collecting statistics first seems to be a time consuming and highly expensive path often leading to nowhere. The possible FOAT procedure to establish the suitable DEPDF, with the detailed numerical examples could be found in Suhir, 2021e.

SSAT offers its own method of study of the complex medical procedures that have significant time span and high memory load. Building human algorithm of such procedures and allowing medical professionals to have externally presented images and steps would reduce the stress and improve reliability of the procedures (Bedny, Bedny, 2019).

Other medical applications of the PDfR concept are addressed in Suhirand Yi, 2017, for medical electron devices ("when reliability is imperative, ability to quantify it is a must"); in Suhir, 2020e and 2021c, to quantify medical undertakings, such as, e.g., clinical cases, which are usually perceived as "unquantifiable", but for which, in the author's opinion, quantification is needed to make these undertakings successful; in Suhir, 2021b and 2022a to "pick the right surgeon".

CONCLUSION

The probabilistic predictive modelling (PPM) concept in ergonomics engineering (EE), addressed in this analysis, is based on a physically meaningful modelling followed by a highly focused and highly cost-effective failure-oriented experimentations (FOEs) geared to the chosen predictive model(s). The concept enables quantifying, on the probabilistic basis, the outcome of a particular human-in-the-loop (HITL) effort and making the never zero probability the human failure low enough and adequate for a particular system and application.

The reliability of human performance is thoroughly studied by the Systemic Structural Activity Theory (SSAT) (Bedny, Bedny, 2018). The reliability of the task performance is closely corelated with its complexity. Reduction of the task complexity leads to reduction of human errors and to improvement in the efficiency of performance. SSAT offers a range of methods such as building a human algorithm of task performance, building a probabilistic event tree, calculating the complexity of the task that allow to identify the critical points of the task performance and improve the efficiency of its design.

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