The System Dynamics Architecture of UTASiMo: a Simulation-Based Task Analysis Tool to Predict Human Error Probability

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***Abstract*—This paper describes the system dynamics architecture of UTASiMo, a simulation-based task analysis tool that simulates the outcomes of task analysis for a system design and estimates task execution times, workload, and human error probability. UTASiMo combines discrete event, agent-based, and system dynamics simulation methods to automatically construct and simulate models that correspond to different scenarios to test prospective human system designs. Here, we focus on the system dynamics model, which captures the causal relationships of factors affecting human error and uses them to assess the overall human error probability of the simulated system (SimHEP). This SimHEP provides a quantitative basis to the simulated human system's evaluation. The present work is a continuation of our previous work on UTASiMo and aims to introduce system dynamics simulation as a potential method to assess human reliability.**

Keywords*— System Dynamics; Task Analysis; Modeling; Human reliability assessment; Simulation; UTASiMo

I. INTRODUCTION

The importance of modeling and simulation of human performance in the field of human reliability analysis (HRA) has been outlined in a variety of studies [1], [2]. More specifically, a fusion of modeling and simulation with HRA can address the dynamic nature and progression of human behavior in a way that most HRA methods fail to achieve. Therefore, the topic of interest in this report is the combination of modeling and simulation with HRA in order to provide a way to estimate human error probabilities.

In previous work, we have presented the agent-based and discrete event architectures of the UTASiMo simulation tool, which automates the modeling process, generates simulation models for task analysis of real world systems, and allows for experimentation with the generated models [3], [4], [5]. The architecture of the tool was decided by following a generic Multi-Method Modeling & Simulation (3M&S) framework which recommends the use of appropriate simulation methods based on the objectives of the simulation study [6], [7]. In this work, we present the human error assessment module of the tool, which is achieved through a system dynamics model. The system dynamics model captures the causal relationships of factors affecting human error and uses them to assess the overall human error probability (HEP) of the simulated system. The SPAR-H HRA method was used to as a basis formulate the system dynamics model and produce estimates for the human error probabilities.

The purpose of this paper is to provide a brief description of the system dynamics HRA model and introduce this simulation approach as a potential method to assess human reliability.

II. HUMAN RELIABILITY ANALYSIS (HRA)

Human error is a key factor associated with accidents that may have consequences to people, systems, and the environment. A common methodology used to analyze human error is HRA. HRA can be defined as a set of qualitative and quantitative methods that assess the impact of human errors on system performance. A variety of HRA approaches have been proposed in the literature including HEART (Human Error Assessment and Reduction Technique), THERP (Technique for Human Error Rate Prediction), and APJ (Absolute Probability Judgement), among others. A typical feature of all approaches is a set of factors "which influence the likelihood of an error occurring" [8]. These factors include influences related to the individual, system, task, or environment. Examples of such factors include experience, task complexity, workload, working conditions, and system quality, among others.

In this work, we utilize the SPAR-H HRA method to build a system dynamics model for estimating human error probabilities of the simulated system. The SPAR-H method [9], [12] was developed for assessing human error probabilities in the nuclear industry. However, the method shows promise for wider application in other domains as the human error probability (HEP) data can be applicable to other domains [10], [11]. Moreover, the SPAR-H method has its base in task analysis and it can be easily adapted to incorporate factors that affect error in multidisciplinary domains. The SPAR-H method utilizes eight performance shaping factors (PSFs). In this study, we utilize five of the factors affecting error (FAE), while considering the other three as nominal and equal to 1. These five factors are the following: available time to complete task, skills and experience, task complexity, quality of any procedures in use, and working conditions.

Each FAE features associated multipliers. For example, high workload would receive a higher multiplier than low workload. A high multiplier increases the likelihood of human error. By assigning multipliers to the different FAE, it is possible to arrive at the simulated system's human error probability (SimHEP). The SimHEP is calculated based on the decomposition of tasks into subtasks.

A HEP for each subtask is calculated in terms of FAE multipliers and base error rate, as in (4). FAE multipliers are obtained from the system dynamics model, which is described in the next section. The list of the multiplier scale used in the system dynamics model for the SimHEP estimation is presented in Table 1.

Table 1
Multipliers used in the system dynamics model for the SimHEP estimation

FAE	FAE Level	Multiplier
Task Complexity	Nominal	1
	Moderately Complex	2
	Highly Complex	5
Available time to complete	Adequate time *(Nominal Workload)*	1
	Adequate time *(Low Workload)*	1.5
	Expansive Time *(High Workload)*	2
	Adequate time *(High Workload)*	5
Skills	Expert *(Skill factor < 1)*	1
	Average *(Skill factor = 1)*	2
	Novice *(Skill factor > 1)*	5
Design quality	Good	0.5
	Nominal	1
	Poor	10
Working conditions	Good	0.8
	Nominal	1
	Poor	2

The base or default error rate is called the nominal human error probability (NHEP). SPAR-H method defines NHEP to be equal to about 0.001 for action tasks and 0.01 for diagnosis tasks.

$$HEP_j = \left(\prod_{i=1}^{5} FAE_i\right) \times NHEP \tag{4}$$

FAEs may increase, decrease or have no effect on human error probability. If the effect of multiple FAEs increases HEP to a value greater than 1, a correction process of SPAR-H is applied, as in (5).

$$HEP_j = \left(\prod_{i=1}^{5} FAE_i - 1\right) \times NHEP + 1 \tag{5}$$

Finally, the overall SimHEP is calculated as the mean error probability of all subtasks based on the number N of tasks that contribute to total error, as in (6).

$$\text{SimHEP} = \frac{\sum_{j=0}^{N} HEP_j}{N} \tag{6}$$

This SimHEP is not a literal probability of error but provides a quantitative basis to the simulated system's evaluation. Based on the SimHEP, each task is classified as low (<0.001), medium (0.001-0.01), or high risk (>0.01) to aid analysts in determining which areas of the system may need redesign.

III. System Dynamics

System dynamics (SD) is a modeling and simulation method that enables the investigation of broader system behaviors. Systems modeled with SD contain elements that are dynamically changing based on various influences. For example, human error, which is an attribute of human agents in such systems, is influenced by the changing system's environment. Therefore, SD is the most appropriate method to model the dynamic nature of such systems and the effect of human error in the reliability of the system [13].

The SD model is incorporated into simulated humans, which are implemented as agents with a statechart inside. The statechart is responsible for the higher level controller of the human's behavior and actions during the task execution process. The statechart was constructed following a framework for extrapolating a hybrid agent-based and system dynamics simulation model from its model-based architecture designed using Systems Modeling Language (SysML) [14]. The SysML diagram illustrated in Fig. 1 has been used as a basis to design the flow of the agent-based statechart that will provide input to the SD model.

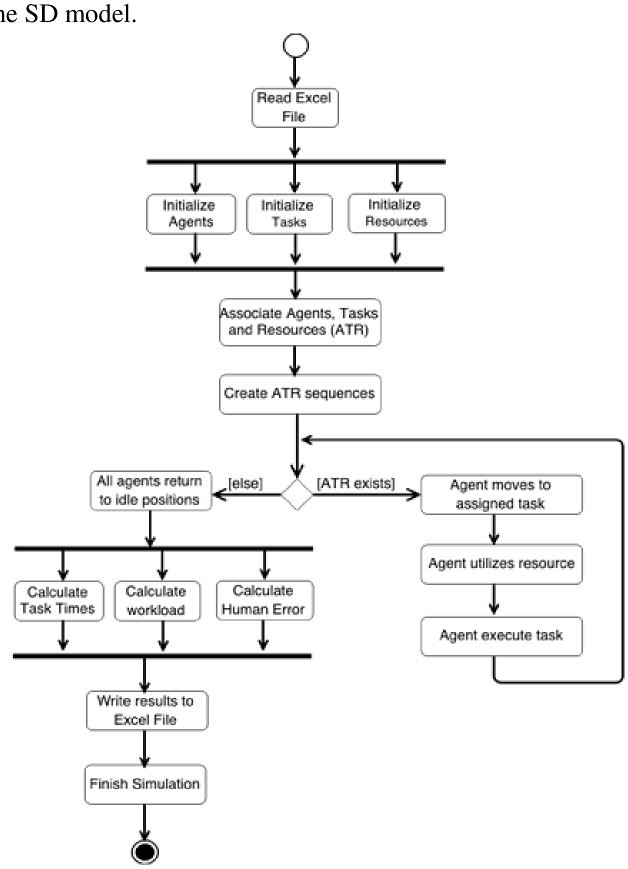

Fig. 1. SysML Activity Diagram used for the construction of the statechart and system dynamics model

The SD model contains causal loops that show interrelations among system parameters and expose feedback loops within the system. Causal loops are developed by correlating pairs of variables where one is dependent and the other independent. The SD model is depicted in Fig. 2.

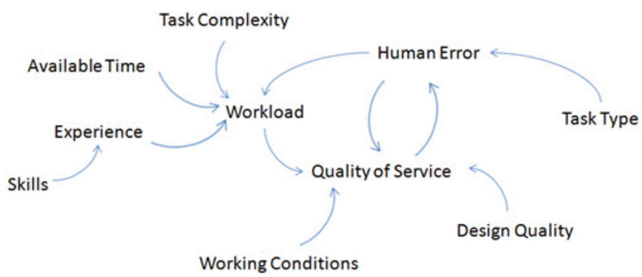

Fig. 2. System dynamics simulation model

The main feedback loop incorporates workload and quality of service. The loop is initiated by changes in agent's available time to perform a task which subsequently influences workload. More specifically, a reduction in available time increases workload. Workload has a negative effect on quality of service which increases human error occurrence and constitutes a reinforcing loop. Quality of service (i.e. medical care) is also affected by working conditions and system/interface design quality [15].

These influences in combination with properties of the task, the environment, and the agent give rise to human error estimates for each task-step. The model then uses these estimates to classify the task as of low, medium, or high criticality.

IV. Discussion and future work

In this work, we presented the system dynamics module of UTASiMo as an approach to estimate HEP. Our future goal is to work on overcoming some limitations of the tool. Currently, the generated system dynamics models are high level representations of the real systems as they were designed to include common elements applicable to any domain. If a more detailed representation of the system is needed, UTASiMo needs to be customized to generate models that include elements relevant to the specific system. Examples of such elements include a more extensive list of FAEs for a specific scenario, among others.

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