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System for Performance Impacts from Conditions in the Environment (SPICE)

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Abstract: In many settings, workers must perform time-critical, outdoor manual actions (MAs) while exposed to the adverse effects of environmental conditions (ECs). These settings include industrial (e.g., oil and gas, nuclear power) and regional (e.g., emergency actions, rescue and recovery). Individually or collectively, ECs may challenge workers by interfering with required (a) motor functions (e.g., impeding effects of flowing water and/or blowing wind), (b) cognitive functions (e.g., degradation of neurophysiological and psychological pathways), and/or (c) collaborative functions (e.g., disrupted oral or electronic communications). This paper delineates a framework—*System for Performance Impacts from Conditions in the Environment* (*SPICE*)—relating ECs to MAs and human performance effects. Our research initially focused on external flooding events that trigger emergency actions at nuclear power plants (NPPs). By characterizing external-flood-causing mechanisms (e.g., local intense precipitation, riverine or coastal processes) and associated hydrometeorological conditions, 11 ECs were identified that may prevail during external flooding events. MAs commonly performed in preparation for and response to flooding events were identified from review of post-Fukushima walkdowns of U.S. NPPs and plant Abnormal Operating Procedures. The MAs were often complex, requiring: (a) multiple steps involving sequential movements or a combination of motor and cognitive functions and processes; (b) performance at multiple task locations; and (c) varying levels of automation, tools, and/or equipment. The MAs were hierarchically decomposed into simpler, discrete, lower-level units—tasks, subtasks, and generic actions (GAs). In turn, GAs were composed of one or more of nine performance demands (PDs)—required human physiological and/or cognitive exertion imposed by performance of a human action. This task decomposition approach facilitated EC impact assessment consistent with approaches in the human performance literature. From comprehensive literature reviews, four levels of performance information were identified for each EC-PD combination: *Quantitative*, *Limits*, *Qualitative*, and *Gap*. In SPICE, impact on a GA is estimated by combining the effects of ECs on constituent PDs, weighted by each PD's relative contribution to the GA. A test application illustrates computations of EC impacts on GAs and aggregation to higher-level task elements (i.e., subtasks, tasks, and MAs).

Keywords: emergency response, environmental condition, human performance modeling, manual action, performance demand

1. Introduction

In many settings, workers need to perform time-critical manual actions (MAs)[1] to protect against hazards from severe natural phenomena (e.g., protecting critical facilities from floods, rescue and recovery following an earthquake). Often, these MAs need to be performed not only indoors but also outdoors. It might be ideal to complete all such MAs before environmental conditions (ECs) accompanying a natural event reach severities that preclude work activities, but several natural phenomena occur without sufficient forewarning (e.g., thunderstorms and earthquakes). As a result, MAs may need to be performed after the event has begun (e.g., floods) or occurred (e.g., earthquakes). Workers consequently may be subject to elevated EC

[1] MAs are a distinct group of inter-related tasks that are performed to achieve an operational goal. A MA is not limited to a physical action performed without the aid of equipment—it may involve operating equipment, installing barriers, or setting up portable equipment.

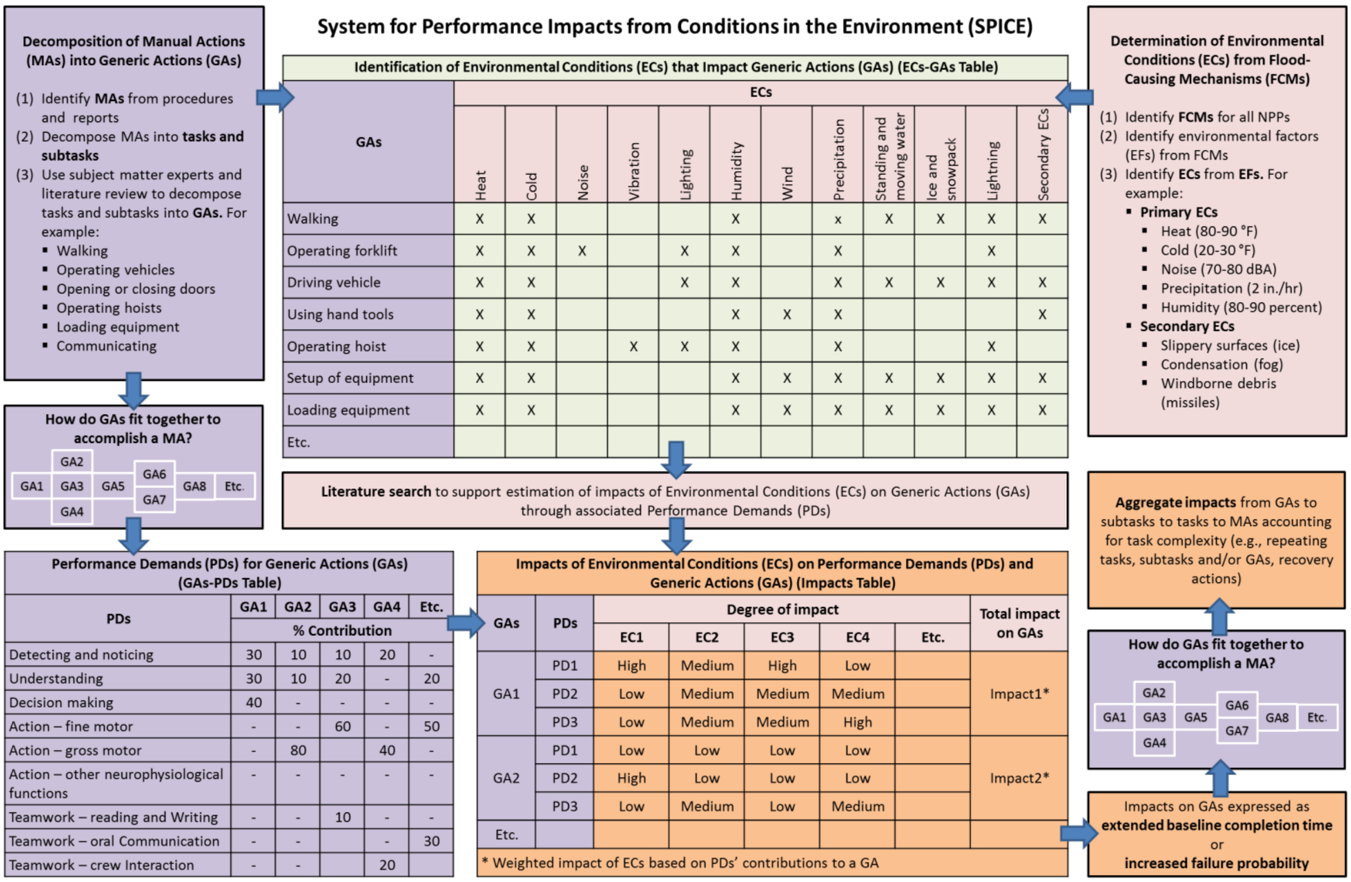

Figure 1. System for Performance Impacts from Conditions in the Environment (SPICE)

severities that adversely affect work performance. ECs may vary both in space (i.e., across locations of MAs) and in time (e.g., with the rise and fall of floodwaters or with temperature fluctuations). Our research initially characterized MAs and ECs across U.S. NPPs that may need to employ Abnormal Operating Procedures (AOPs) during external flooding events (Prasad et al., 2017). The *System for Performance Impact from Conditions in the Environment* (*SPICE*) is a framework that was developed to (a) illustrate relationships among ECs, MAs, and human performance effects and (b) provide the basis for computationally estimating the impacts of ECs on MAs.

SPICE has five basic elements: (a) decomposition of MAs into a hierarchy of simpler task elements including tasks, subtasks, and GAs;[2] (b) characterization of ECs associated with the adverse natural phenomenon; (c) characterization of performance demands (PDs);[3] (d) characterization of the potential impacts of ECs on PDs; and (e) aggregation of the impacts of ECs on PDs to GAs and higher-level task elements. Figure 1 illustrates the relationships. MA performance impact is assessed as an increase in: (a) completion time, (b) error rate, and/or (c) probability of failure.

1.1 Manual Actions

To identify and characterize the flood-protection and mitigation (FPM) MAs, Prasad et al. (2017) reviewed (a) NRC Staff Assessments of Flooding Walkdown Reports[4] for 60 NPP sites and (b) available individual NPP procedures (e.g., AOPs). This review yielded a list of common MAs expected to appear in FPM procedures across U.S. NPP sites. The identified MAs are not specific to the nuclear power industry and may be common to responses for several adverse natural phenomena.

[2] An individual component of a task or subtask that is sufficiently simple to evaluate the impact of ECs on human performance.
[3] Performance demands are required human physiological and/or cognitive exertions imposed by performance of a human action.
[4] Following the Fukushima accident, all U.S. NPPs performed flooding walkdowns to determine if their FPM features and procedures were adequate. The NRC reviewed the Flooding Walkdown Reports and published a corresponding Staff Assessment.

Table 1. Examples of Manual Actions (MAs) and Generic Actions (GAs)

MAs	GAs
Deploy sandbags; build berms	Walk
Place flood barriers	Operate a transport vehicle, forklift, or frontend loader
Clear debris from intake	Manually lift and move heavy materials or equipment
Set and operate diesel generators	Use hand tools
De-energize and adjust electrical power	Communicate electronically or non-electronically

MAs were often complex: (a) consisting of multiple steps, involving sequential movements and/or combinations of motor and cognitive functions and processes, and (b) requiring movements between task locations and varying levels of automation and/or tools or equipment. We decomposed the MAs hierarchically into simpler, discrete, lower-level task elements (i.e., tasks, subtasks, and GAs). The decomposition approach represented MAs at the level of detail that provided (a) a better understanding of involved human actions/performance and (b) a more direct correspondence to the impacts of ECs on aspects of human performance described in the research literature. Examples of MAs and GAs are listed in Table 1.

1.2 Environmental Conditions

Prasad et al. (2017) updated and broadly extended NUREG/CR-5680, *The Impact of Environmental Conditions on Human Performance* (Vols. 1 and 2), which had reviewed mid-1990s research regarding the impacts of five ECs[5] on human performance (Echeverria et al., 1994). Drawing on experience from the NRC's NPP siting and licensing reviews, Prasad et al. identified six additional ECs that (a) often accompanied floods and (b) were relevant to the performance of MAs. In all, Prasad et al. addressed: *heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning*. Pertinently, Prasad et al. recognized that: (a) ECs can occur in combination (e.g., heat with humidity, cold with wind and precipitation); (b) secondary ECs can occur with one or more primary ECs (e.g., slippery surfaces with precipitation or ice and snowpack, debris with moving water or wind); and (c) EC severities can vary during the performance of MAs. Figure 1 lists some examples of secondary ECs.

1.3 Performance Demands

Prasad et al. (2017) identified and assembled pertinent literature using (a) the review provided by Echeverria et al. (1994), (b) forward-searched databases that represented the most relevant discipline areas,[6] and (c) key literature recommendations from cognizant researchers. Overall, much of the research investigated EC effects by discretizing and categorizing aspects of human performance. Prasad et al. (2017) synthesized three such categorizations (i.e., the Echeverria et al., 1994 *performance abilities*; O'Brian et al., 1992 *taxons*; and Whaley et al., 2016 *macro-cognitive functions*) as well as one employed in current NRC human reliability analyses into a taxonomy of nine PDs:

- *Detecting and noticing* – attention; memory; vigilance; switching; acuity; perception and threshold perception; and sensation and visual recognition
- *Understanding* – pattern recognition; discrimination; understanding; evaluating; hypothesizing; diagnosing; and integrating
- *Decision-making* – reasoning; computing; interpreting; classifying; goal setting; planning; adapting; and evaluating and selecting options
- *Action, fine motor skills* – discrete and motor continuous; and manual dexterity
- *Action, gross motor skills* – heavy and light
- *Action, other neurophysiological functions* – unaddressed by other PDs
- *Teamwork, reading and writing*
- *Teamwork, communication* – face-to-face and electronic
- *Teamwork, coordination* – cooperation; crew interaction; and command and control.

Each GA is represented by varying proportions of the nine PDs as illustrated in Figure 2. ECs, individually or collectively, affect PDs and thereby, the GA.

[5] The five environmental conditions addressed in NUREG/CR-5680 were heat, cold, noise, vibration, and lighting.

[6] Disciplines include cognitive and experimental psychology, human factors, industrial engineering, industrial hygiene, environmental and occupational health, environmental physiology, and medicine.

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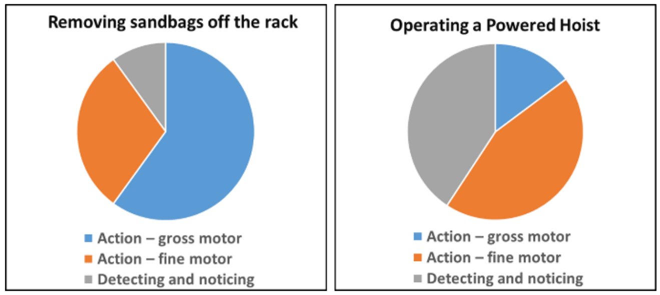

Figure 2. Nominal illustration of two GAs requiring different combinations of PDs

1.4 Impacts of ECs on PDs

To identify approaches for estimating the impacts of ECs on PDs, Prasad et al. (2017) searched for relevant studies that addressed primary and secondary ECs effects, especially in terms related to the PDs in the above taxonomy. The research has largely focused on ECs that have the greatest potential to affect: (a) workers in industrial settings (e.g., heat, noise, vibration, lighting), (b) military personnel (e.g., heat, cold, noise), and (c) vehicle operators (e.g., lighting, precipitation). Additionally, investigations illuminated common mechanisms by which physiological, cognitive, and affective systems broadly respond to various ECs (e.g., heat, cold, lighting, noise, vibration). Some applications-oriented research had also focused on developing equations and models that characterize the mechanical effects of physical forces (e.g., pressure, drag, and friction) on performance under prevailing ECs (e.g., wind, moving water, ice and snowpack). Prasad et al. (2017) clearly identified two broad categories of EC effects on human performance: (a) physical forces that mechanically interfere with motor functions (e.g., the impeding effects of flowing water and/or blowing wind) and (b) internal responses that primarily act through neurophysiological and psychological pathways (e.g., slowing of motor and cognitive functions under elevated heat or cold). Ultimately, Prasad et al. (2017) categorized the information available on performance impacts using four levels that reflected their potential utility:

- *Level 1*: directly-applicable information to determine the quantitative impact of an EC on human performance (e.g., for ECs such as wind and standing and moving water that primarily act via a physical force)
- *Level 2*: information of some applicability in determining the degree of impact of an EC on human performance (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, a worker cannot perform an activity at all)
- *Level 3*: qualitative information – general agreement exists in the literature that the EC affects human performance, but the measured impacts are not reported in literature, not even for severity limits
- *Level 4*: absence of information (a research gap).

For the 99 EC-PD combinations (i.e., 11 ECs potentially affecting 9 PDs), Levels 1-4 information was available for 8, 29, 43, and 44 combinations, respectively.[7] The literature search did not identify any large-scale ongoing or upcoming research programs from which major advances might be anticipated in the near future. Consequently, it appears likely that progress will be largely incremental in the upcoming years. This may be particularly true for combinations of multiple ECs that can affect a PD. Nonetheless, impact factors[8] have long been productively used for estimating the effects of an EC on a PD with the current information base. The effects of several ECs on a PD have likewise long been productively estimated using additive, multiplicative, or power function combination schemes as discussed in the following section.

1.5 Aggregation of Impacts

EC impacts on PDs are aggregated to GAs, subtasks, tasks, and MAs (Figure 3). Prasad et al. (2017) used performance time as the measure. Following their approach, the baseline time[9] for the k^{th} GA is expressed as $TG_k = \sum_{i=1}^{9} T_{i,k}$, where $T_{i,k}$ is the performance time associated with i^{th} PD within the GA. The affected time for the k^{th} GA is then

[7] The counts for the four levels do not add to 99 because for some of the EC-PD combinations, multiple levels are assigned reflecting variability in the level of quantification available for different elements of human performance composing a PD.
[8] Impact factor is a numerical measure of the increase in time to perform or the increase in error rate for performing a GA. Because GAs consist of PDs, EC impact on a GA is obtained by multiplying the relative contributions of the PDs by the corresponding impact factor.
[9] Baseline time is the time required to complete a GA unaffected by adverse effects of ECs.

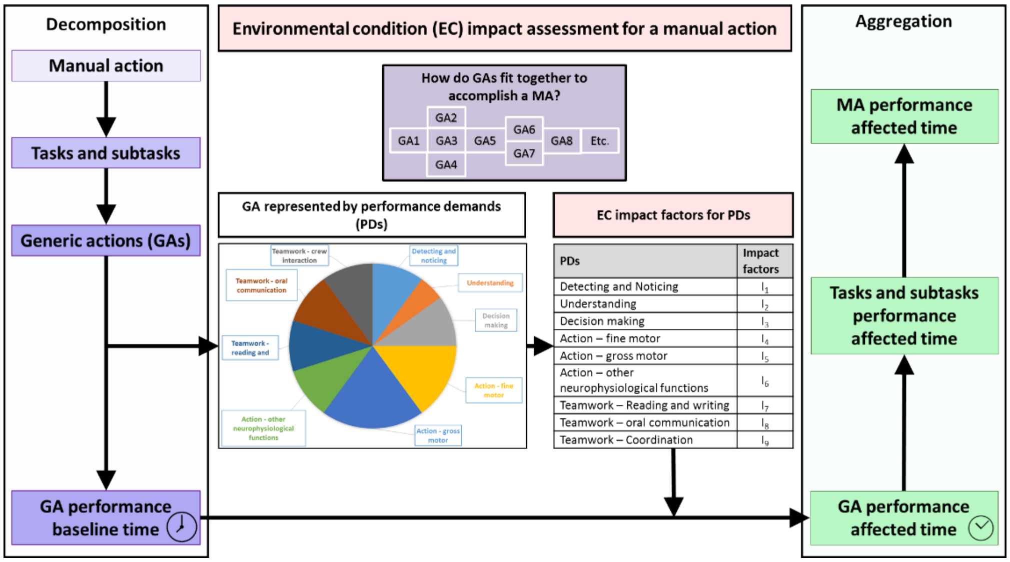

Figure 3. Impact assessment through MA decomposition and GA aggregation

expressed as $TG_k^* = \sum_{i=1}^{9}(I_{i,k}T_{i,k})$, where $I_{i,k}$ are the impact factors for the i^{th} PD within the GA. When multiple ECs affect a GA simultaneously, $I_{i,k}$ can be expressed as $\sum_{j=1}^{n_e} I_{i,j,k}$ for the additive, $\prod_{j=1}^{n_e} I_{i,j,k}$ for the multiplicative, and $\prod_{j=1}^{n_e}(I_{i,j,k})^{\alpha_j}$ for the power function combination scheme with $j = 1,2,3, \dots n_e$ denoting the j^{th} of n_e ECs acting simultaneously and α_j denoting the exponents for the ECs in the power function. The affected time for the k^{th} GA can also be expressed as $TG_k^* = \sum_{i=1}^{9}(I_{i,k}w_iTG_k) = (\sum_{i=1}^{9} I_{i,k}w_i)TG_k$, where w_i are the weights or the relative contributions of the PDs within the GA.

Following the decomposition sequence back up the task hierarchy, the affected time for performing a subtask or task is expressed as $TS_l^* = \sum_{k=1}^{n_G} TG_k^*$ and for a MA as $TA_o^* = \sum_{l=1}^{n_S} TS_l^*$, where n_G GAs constitute a subtask or task, and n_S subtasks or tasks constitute the o^{th} MA. The aggregation process is illustrated in Figure 3.

Prasad et al. (2017) acknowledged that this formulation assumes that GAs, subtasks, and tasks comprising a MA are performed sequentially. However, it is obvious that other task performance orders are possible, including those that involve parallel and recovery tasks as well as loops and interdependencies. The above formulation can, and has been, generalized to computationally address other task performance orders as demonstrated by Prasad et al. (2017).

2. Test Application of SPICE and Conclusions

Prasad et al. (2017) illustrated the application of SPICE to one task of a MA, namely "Fastening Flood Barriers." Fastening one flood barrier required four subtasks that in turn required 3, 1, 4, and 2 GAs (Table 2, Columns 1 and 2). They estimated the baseline time for each GA (Table 2, Column 3) and the relative contribution of PDs to the GAs (Table 2, PD Weights w_1-w_9). The MA was assumed to be affected by only one EC—heavy precipitation (rain). They estimated the impact factor for each PD (Table 2, Second-to-Last Row). The affected time for the task was determined by multiplying PD times by the corresponding impact factors and aggregating. The performance time increased 23 percent, from 120 to 147.7 min.

The test application was intentionally simple to demonstrate the utility of SPICE. Incorporation of multiple simultaneous ECs, time variation of ECs, interactions among multiple crews, and task complexity is not precluded in SPICE. However, to incorporate these more realistic aspects of MAs and ECs, a dynamic task network modeling approach is needed. Currently available tools (e.g., U.S. Army Research Laboratory's Improved Performance Research Integration Tool, IMPRINT; ARL, 2017) can be adapted to analyze MAs and estimate performance impacts from ECs.

The estimates of MA baseline times, PD weights, and EC-PD impact factors would require further research and collaboration with and/or elicitation from subject matter experts and experienced workers. Significant variability and uncertainty is expected to exist for all of these estimates. Explicit characterization of uncertainty using Monte Carlo approaches can assist decision-makers in planning for and responding to emergencies.

Finally, SPICE is not limited to hazards from floods or to MAs performed at NPPs. Estimates of adverse effects of ECs accompanying any natural or anthropogenic phenomenon in many settings can be addressed by SPICE.

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Table 2. Fastening a Flood Barrier Impact Estimation Overview

			Performance Demand Weights									
						Action			Teamwork			
Subtask	GAs	Baseline Time (min)	w_1 Detecting and Noticing	w_2 Understanding	w_3 Decision-Making	w_4 Fine Motor	w_5 Gross Motor	w_6 Other	w_7 Reading/writing	w_8 Oral Comm.	w_9 Crew Interaction	Affected Time (min)
Position forklift	Walking	5	0.25	0	0	0	0.75	0	0	0	0	5.75
	Getting in forklift	1	0.25	0.25	0	0	0.5	0	0	0	0	1.15
	Driving	9	0.17	0.17	0.17	0.5	0	0	0	0	0	11.10
Load plates onto forklift	Loading plates	15	0.17	0.17	0.17	0.5	0	0	0	0	0	18.50
Position plates against structure wall with forklift	Positioning plates/driving	10	0.17	0.17	0.17	0.5	0	0	0	0	0	12.33
	Communicating the position	10	0	0	0	0	0	0	0	0.5	0.5	12.50
	Pinning with forklift	20	0.17	0.17	0.17	0.5	0	0	0	0	0	24.67
	Manually adjusting	20	0.33	0	0	0.33	0.33	0	0	0	0	24.67
Drill holes and secure with fasteners	Drilling (hand tool)	15	0.33	0.33	0	0.33	0	0	0	0	0	18.50
	Bolting (hand tool)	15	0.33	0.33	0	0.33	0	0	0	0	0	18.50
Impact Factor for Heavy Precipitation			1.3	1.1	1.1	1.3	1.1	1	1	1.2	1.3	
Total Time (min)		120										147.67

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