Webinar Handout:
Tools used in Naturalistic Decision Making (NDM) and in Resilience Engineering (RE)

Prepared by Gary Klein, PhD, and Sudeep Hegde, PhD for attendees of the webinar: "Tools of Practice: Points of Convergence and Divergence", November 12th 2020

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Naturalistic Decision Making Tools

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This memo contains an initial listing of NDM tools, for use by practitioners and colleagues.

We are not trying to achieve anything that is comprehensive or scholarly. The memo is intended merely as a quick survey. And as you look at the tools listed below you may have disagreements about whether some of the tools belong with NDM or not. The edges of NDM are blurry, but that should not prevent us from attempting to catalog what we have created.

By "tool," we mean something you can use to get a job done. So we have included conceptual models as tools. But we are not including tools that are primarily designed for doing laboratory research involving controlled experiments.

The following colleagues helped to identify all these tools (in alphabetical order): Cindy Dominguez, Julie Gore, Robert Hoffman, Devorah Klein, Laura Militello, Brian Moon, Emilie Roth, Jan Maarten Schraagen, and Neelam Naikar. Adam Zaremsky added the short descriptors and references.

Knowledge Elicitation:

a. Critical Decision Method (CDM): A knowledge elicitation technique that uses a set of cognitive probes to determine the basis for situation assessment and decision making during nonroutine incidents in multiple sweeps of the incident in retrospection.

> Klein, G. A., Calderwood, R., & MacGregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on systems, man, and cybernetics*, *19*(3), 462-472.
>
> Hoffman, R. R., Crandall, B., & Shadbolt, N. (1998). Use of the critical decision method to elicit expert knowledge: A case study in the methodology of cognitive task analysis. *Human factors*, *40*(2), 254-276.

b. Situation Awareness Record: Specific changes in cue usage and goals in an expert's understanding of the dynamics of a particular case.

> Klein, G. A., Calderwood, R., & Macgregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on systems, man, and cybernetics*, *19*(3), 462-472.

c. Applied Cognitive Task Analysis (ACTA): A streamlined set of interview methods for identifying cognitive demands and skills needed to perform a task proficiently.

Militello, L. G., & Hutton, R. J. (1998). Applied cognitive task analysis (ACTA): a practitioner's toolkit for understanding cognitive task demands. *Ergonomics*, *41*(11), 1618-1641.

d. Knowledge Audit (from ACTA): A set of probes organized to capture the most important knowledge categories recognized as characteristic of expertise.

Militello, L. G., & Hutton, R. J. (1998). Applied cognitive task analysis (ACTA): a practitioner's toolkit for understanding cognitive task demands. *Ergonomics*, *41*(11), 1618-1641.

Klein, G., & Militello, L. (2004). The knowledge audit as a method for cognitive task analysis. *How professionals make decisions*, 335-342.

e. Cognitive Audit: A method to assess and identify which specifically trainable cognitive skills an instructor might want to address.

Klein, G. (2017) The Cognitive Audit. *Seeing what others don't, Psychology Today*, https://www.psychologytoday.com/us/blog/seeing-what-others-dont/201707/the-cognitive-audit

f. Concept Maps: A tool for organizing knowledge, by showing the relationships of events and objects between which a perceived regularity exists, through the use of connecting lines, circles, and boxes of some type.

Novak, J. D., & Cañas, A. J. (2006). The theory underlying concept maps and how to construct them. *Florida Institute for Human and Machine Cognition*, *1*(1), 1-31.

Novak, J. D., & Canas, A. J. (2007). Theoretical origins of concept maps, how to construct them, and uses in education. *Reflecting Education*, *3*(1), 29-42.

Cognitive Specifications and Representation:

a. Cognitive Requirements Table: A format for practitioners to focus on the analysis of intended project goals, with headings based on the types of information needed to develop a new course or design a new system.

Militello, L. G., & Hutton, R. J. (1998). Applied cognitive task analysis (ACTA): a practitioner's toolkit for understanding cognitive task demands. *Ergonomics*, *41*(11), 1618-1641.

b. Use of Cognitive Requirements to guide training and design: A use of Naturalistic Decision-Making cognitive frameworks to more accurately describe the processes involved in real-world decision making, to help decision makers with what they are actually trying to do.

Militello, L. G., & Klein, G. (2013). Decision-centered design. *The Oxford handbook of cognitive engineering*, 261-271.

Militello, L. G., Dominguez, C. O., Lintern, G., & Klein, G. (2010). The role of cognitive systems engineering in the systems engineering design process. *Systems Engineering*, *13*(3), 261-273.

c. Critical Cue Inventory: A collection of all of the informational and perceptual cues that are pinpointed in critical decision interviews.

Klein, G. A., Calderwood, R., & Macgregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on systems, man, and cybernetics*, *19*(3), 462-472.

d. Cognimeter: A system for visual monitoring of a user's mental state, assessing in real time human emotion, levels of mental workload and stress.

Chrenka, J., Hotton, R.J. B., Klinger, D. W., & Anastasi, D. (2001). The cognimeter: Focusing cognitive task analysis in the cognitive function model. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 4,* 1738-1742.

e. Integrated Cognitive Analyses for Human-Machine Teaming (ICA-HMT): A strategy for facilitating human-machine teaming consisting of activities to analyze function allocation trade space, analyze operational demands and work requirements, analyze interdependencies between humans and automation, evaluate alternative options with human performance modeling/simulation, and identify and evaluate alternative function allocation and crewing options.

Ernst, K., Roth, E., Militello, L., Sushereba, C., DiIulio, J., Wonderly, S., ... & Taylor, G. (2019). A strategy for determining optimal crewing in future vertical lift: Human-automation function allocation. *Proceedings of the Vertical Lift Society's 75th Annual Forum & Technology Display, Philadelphia, PA.*

Sushereba, C. E., Diiulio, J. B., Militello, L. G., & Roth, E. (2019, November). A tradespace framework for evaluating crewing configurations for future vertical lift. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 63, No. 1, pp. 352-356). Sage CA: Los Angeles, CA: SAGE Publications.

f. Contextual Activity Templates: A representation for characterizing activity in work systems that can be decomposed into both work situations and work functions, by capturing all of the combinations of work situations, work functions and control tasks that are possible.

Naikar, N., Moylan, A., & Pearce, B. (2006). Analyzing activity in complex systems with cognitive work analysis: concepts, guidelines and case study for control task analysis. *Theoretical Issues in Ergonomics Science*, *7*(4), 371-394.

g. Diagram of Work Organization Possibilities: A diagram with multiple features for complex sociotechnical systems including: showcasing what work demands an actor *can* be responsible for, depiction of the fundamental boundaries on the allocation or distribution of work demands from which various possibilities may be derived, with these possibilities regarded as emergent.

> Naikar, N., & Elix, B. (2016). Integrated system design: Promoting the capacity of sociotechnical systems for adaptation through extensions of cognitive work analysis. *Frontiers in psychology*, *7*, 962.

Training:

a. ShadowBox: A training approach that allows trainees to learn how experts make sense of situations, what they pay attention to, why they make their choices, and what their mental models are, all without the expert having to be present.

> Klein, G., & Borders, J. (2016). The ShadowBox approach to cognitive skills training: An empirical evaluation. *Journal of Cognitive Engineering and Decision Making*, *10*(3), 268-280.

> Klein, G., Hintze, N., & Saab, D. (2013, May). Thinking inside the box: The ShadowBox method for cognitive skill development. In *Proceedings of the 11th International Conference on Naturalistic Decision Making* (pp. 121-124).

b. Tactical Decision Games/Decision Making Exercises: Tactical Decision Games (TDGs) are simple, fun, and effective exercises to improve one's decision making ability and tactical acumen by repeatedly playing through problems to learn to make decisions better as well as better decisions.

> Schmitt, J. F. (1994). *Mastering Tactics: A tactical decision games workbook*. Marine Corps Association.

c. Artificial Intelligence Quotient (AIQ) for helping users operate AI systems: A set of tools for human-machine systems designed to increase the human operators' knowledge and understanding of the technologies explainability.

> Klein, G. (2020) AIQ: Artificial Intelligence Quotient. *Seeing what others don't, Psychology Today*, https://www.psychologytoday.com/us/blog/seeing-what-others-dont/202007/aiq-artificial-intelligence-quotient

d. On-the-Job Training: A cognitive model of training that has one primary function, learning management, and six subordinate functions of a provider: setting/clarifying goals, providing instruction, assessing trainee proficiency and diagnosing barriers to progress, sharing expertise, setting a climate conducive to learning, and promoting ownership of the learning process and performance of the trainee.

Zsambok, C. E., Kaempf, G. L., Crandall, B., & Kyne, M. (1997). *A Comprehensive Program to Deliver On-The-Job Training (OJT)*. Klein Associates Inc Fairborn OH.

e. CAARGO: A new training tool designed to improve the ability of decision makers in the oil, gas, and petrochemical industries to help plant operators build richer mental models and more effective mindsets, helping them to make better decisions.

Borders, J., Klein, G., & Besuijen, R. (2020) Mental Models: Cognitive After-Action Review Guide for Observers Video Final Report. *Center for Operator Performance* (Unpublished Report).

Design:

a. Decision-Centered Design: A framework focused on utilizing CTA methods to identify the tough, key decisions of performance, and then create the design of the technology, training, and processes based upon those identified requirements.

Militello, L. G., & Klein, G. (2013). Decision-centered design. *The Oxford handbook of cognitive engineering*, 261-271.

b. Principles for Collaborative Automation: A replanning tool designed to support human operators to collaborate with an automated support collaborative planner, where the planner was created to operate with observable and directable functioning, with a shared frame of reference to the human operator, to allow for work to be completed iteratively and jointly.

Scott, R., Roth, E., Truxler, R., Ostwald, J., & Wampler, J. (2009, October). Techniques for effective collaborative automation for air mission replanning. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 53, No. 4, pp. 202-206). Sage CA: Los Angeles, CA: SAGE Publications.

c. Principles of Human-Centered Computing: A set of methodologies applicable in any context when humans directly interact with computing devices and systems, that facilitates any personal, social or cultural aspects, and addresses issues such as information design, human-information interaction, human-computer interaction, human-human interaction, and the relationships between computing technology and art, social, and cultural issues.

Hoffman, R. R., Roesler, A., & Moon, B. M. (2004). What is design in the context of human-centered computing?. *IEEE Intelligent Systems*, *19*(4), 89-95.

Zhang, J., Patel, V. L., Johnson, K. A., & Smith, J. W. (2002). Designing human-centered distributed information systems. *IEEE intelligent systems*, *17*(5), 42-47.

Evaluation:

a. Sero!: A software platform for conducting concept mapping-based assessments, allowing users to create their own concept maps, and then providing evaluation tools to determine the quality of a created concept map, and offer suggestions for improvements and next steps.

Moon, B., Johnston, C., & Moon, S. (2018). A Case for the Superiority of Concept Mapping-Based Assessments for Assessing Mental Models. In *Concept Mapping: Renewing Learning and Thinking. Proceedings of the 8th Int. Conference on Concept Mapping, Medellín, Colombia: Universidad EAFIT*.

b. Concept Maps: A tool for organizing knowledge, showing the relationships of events and objects between which a perceived regularity exists, through the use of connecting lines, circles, and boxes of some type. (Concept Maps are also listed above as a knowledge elicitation method.)

Novak, J. D., & Cañas, A. J. (2006). The theory underlying concept maps and how to construct them. *Florida Institute for Human and Machine Cognition*, *1*(1), 1-31.

Novak, J. D., & Canas, A. J. (2007). Theoretical origins of concept maps, how to construct them, and uses in education. *Reflecting Education*, *3*(1), 29-42.

c. Decision Making Record for Performance Reviews: An alternative method to standard performance reviews, where the reviewer and reviewee independently draw up and evaluate a list of decisions made in the prior year, focusing attention to the quality of the decision itself, not the decision maker.

Klein, G (2019). The Decision Scorecard. *Seeing what others don't, Psychology Today*, https://www.psychologytoday.com/us/blog/seeing-what-others-dont/201509/the-decision-scorecard

d. Work-Centered Evaluation (method for technology evaluation): An evaluation framework that focuses on a support system's usability, usefulness, and impact in supporting human performance in complex work environments.

Eggleston, R. G., Roth, E. M., & Scott, R. (2003, October). A framework for work-centered product evaluation. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 47, No. 3, pp. 503-507). Sage CA: Los Angeles, CA: SAGE Publications.

Teamwork:

a. SA Calibration Questions: A process for team members to share SA information, which may include a group exercise of questioning norms, checking for conflicting information, setting up coordination and prioritization of tasks, and establishing contingency planning.

Klinger, D. W., & Klein, G. (1999). Emergency response organizations: An accident waiting to happen. *Ergonomics in Design*, *7*(3), 20-25.

b. Cultural Lens Model: A model that captures the nature and origin of international cognitive differences, usually arising from a group's origin in a specific physical and social ecology and provides mechanisms for increasing comprehension and effectiveness in the face of these cognitive differences.

> Klein, H. A. (2004). Cognition in natural settings: The cultural lens model. *Cultural ergonomics*. 249-280.

Risk Assessment:

a. Pre-mortem: A managerial strategy at the outset of a project where a team engages in a hypothetical presumption that it has failed spectacularly, subsequently working backwards to identify what weaknesses or threats to the project they can avoid.

> Klein, G. (2007). Performing a project premortem. *Harvard business review*, *85*(9), 18-19.

Measurement:

a. Macrocognitive Measures: The six main macrocognitive functions are identified as, decision making, sensemaking, problem detection, planning, adapting, and coordinating.

> Klein, G. (2018). Macrocognitive measures for evaluating cognitive work. *Macrocognition Metrics and Scenarios* 47-64. CRC Press.

b. Performance assessment by order statistics: A novel method of statistical data analysis for assessing the learnability of cognitive work methods.

> Hoffman, R. R., Marx, M., Amin, R., & McDermott, P. L. (2010). Measurement for evaluating the learnability and resilience of methods of cognitive work. *Theoretical Issues in Ergonomics Science*, *11*(6), 561-575.

c. Scales for Explainable Artificial Intelligence: A means to explain a computational system to decision makers who rely on Artificial Intelligence, so that they may decide on the reasonableness of that system.

> 1. Trust: A series of active exploration measures aimed at maintaining an appropriate context-dependent expectation for users to know whether, when and why to trust or mistrust an XAI system.
>
> 2. Explanation Satisfaction: The degree to which users feel that they understand the AI system or process being explained to them.
>
> 3. Explanation Goodness: Utilizing factors such as clarity and precision, a checklist for researchers to either try and design goodness into the explanation that their XAI system generates, or to evaluate a priori goodness of the explanations generated.

4. Quality of Mental Models: A measure to assess the "goodness" (i.e., correctness, comprehensiveness, coherence, usefulness) of a users' mental model in regard to an XAI system, by calculating the percentage of concepts, relations, and propositions that are in a user's explanation that are also in an expert's explanation.

Hoffman, R. R., Mueller, S. T., Klein, G., & Litman, J. (2018). Metrics for explainable AI: Challenges and prospects. *arXiv preprint arXiv:1812.04608*.

Conceptual Descriptions:

a. RPD model: A decision-making model that explains how people use situation assessment to generate plausible courses of action, while simultaneously using mental simulation to evaluate generated courses of action.

Klein, G., Calderwood, R., & Clinton-Cirocco, A. (2010). Rapid decision making on the fire ground: The original study plus a postscript. *Journal of Cognitive Engineering and Decision Making, 4*, 186-209.

b. Computational model of RPD: A combination of the conceptual RPD model with computer programming to simulate realistic expert decision making.

Hutton, R. J., Warwick, W., Stanard, T., McDermott, P. L., & McIlwaine, S. (2001, October). Computational model of recognition-primed decisions (RPD): improving realism in computer-generated forces (CGF). In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 45, No. 26, pp. 1833-1837). Sage CA: Los Angeles, CA: SAGE Publications.

c. Data/Frame model of sensemaking: A description of the ever-changing and interconnected relationship between data, which is available information, and cognitive frames, which are explanatory structures that define entities by explaining their relationship to other entities.

Klein, G., Phillips, J. K., Rall, E. L., & Peluso, D. A. (2007, May). A data-frame theory of sensemaking. In *Expertise out of context: Proceedings of the sixth international conference on naturalistic decision making* (pp. 113-155). New York, NY: Lawrence Erlbaum Assoc Inc.
Moore, D. T., & Hoffman, R. R. (2011). Data-frame theory of sensemaking as a best model for intelligence. *American Intelligence Journal*, *29*(2), 145-158.

d: Computational model of D/F: Use of the Data Frame model of sensemaking in the creation of computational simulations for machine systems to support human decision makers, utilizing key characteristics of computational cognition, including ontology representation, network theory, and reasoning processes with recursive feedback.

Kodagoda, N., Pontis, S., Simmie, D., Attfield, S., Wong, B. W., Blandford, A., & Hankin, C. (2017). Using machine learning to infer reasoning provenance from user interaction log data: based on the data/frame theory of sensemaking. *Journal of Cognitive Engineering and Decision Making*, *11*(1), 23-41.

Codjoe, E. A. A., Ntuen, C., & Chenou, J. (2010). A case study in sensemaking using Data/Frame Model. In *IIE Annual Conference. Proceedings* (p. 1). Institute of Industrial and Systems Engineers (IISE).

e. Management-by-Discovery/Flexecution: Intertwined concepts, both revolving around good managers being able to change goals as they go based on discoveries, by trying to learn more about those goals even as they pursue them.

Klein, G. (2007) Flexecution as a paradigm for replanning, part 1. *IEEE Intelligent Systems 22.5*, 79-83.

Klein, G. A. (2011) *Streetlights and shadows: Searching for the keys to adaptive decision making*. MIT Press.

f. Triple Path Model of Insight: This model describes three paths that can lead people to having insights: contradictions, connections, and creative desperation.

Klein, G. (2013) *Seeing what others don't: The remarkable ways we gain insights*. Public Affairs.

g. Naturalistic Models of Explaining: Three models of how explanations are formed when a person tries to explain the reasons for the decisions, actions, or workings of a device to another person: Local explaining, global explaining and self-explaining.

Klein, G., Hoffman, R., & Mueller, S. (2019) Naturalistic Psychological Model of Explanatory Reasoning: How People Explain Things to Others and to Themselves. *International Conference on Naturalistic Decision Making, San Francisco, California*

h. Problem Detection Model: A model of sensemaking, where in the process by which a person becomes aware of a problem, or an unexpected or undesirable direction of a situation, that person begins to reconceptualize the situation they found themselves in.

Klein, G., Pliske, R. M., Crandall, B., & Woods, D. (2005). Problem detection. *Cognition, Technology, and Work, 7*, 14-28.

Resilience Engineering Tools and Frameworks

Sudeep Hegde

The purpose of this memo is to start a listing of tools available from the RE literature, so the NDM community can become familiar. These tools include methods, techniques, instruments or frameworks developed in Resilience Engineering, and used by researchers and domain practitioners (e.g. safety managers). Some of these tools are borrowed from other academic disciplines and schools of thought and adapted by RE researchers and practitioners. Note: This is not meant to be an exhaustive list, but a representation of tools that are frequently used, or recently published in the RE literature.

A note of thanks to Riccardo Patriarca for his help in identifying some of the tools in this list.

Knowledge Elicitation:

a. *Interviewing: Critical Incident Technique (CIT) and the Critical Decision Method (CDM):* The CIT and CDM are both knowledge elicitation techniques that involve a series of steps or 'sweeps' to unravel a practitioner's decision making during nonroutine incidents. Studies in RE have adapted the CIT and CDM to include probes for identifying aspects of resilient functioning in both, routine and nonroutine events that occur in everyday work. Examples of such studies include:

STELLA: Report from the SNAFUcatchers Workshop on Coping with Complexity: https://snafucatchers.github.io/

Hegde, S., Hettinger, A. Z., Fairbanks, R. J., Wreathall, J., Krevat, S. A., & Bisantz, A. M. (2020). Knowledge Elicitation to Understand Resilience: A Method and Findings From a Health Care Case Study. *Journal of Cognitive Engineering and Decision Making, 14*(1), 75–95.

b. *Resilience Engineering Tool to Improve Patient Safety (RETIPS):* A self-reporting tool designed for frontline healthcare workers to share lessons and narratives related adaptation in everyday work.

Hegde, S., Hettinger, A.Z., Fairbanks, R.J., Wreathall, J., Krevat, S.A., Jackson, C.D. & Bisantz, A.M. (2020). Qualitative Findings from a Pilot Stage Implementation of a Novel Organizational Learning Tool Toward Operationalizing the Safety-II Paradigm in Health Care. *Applied Ergonomics, 82*. Advance online publication. https://doi.org/10.1016/j.apergo.2019.102913

NOTE: Many RE projects have conducted knowledge elicitation from participants using ethnographic and unstructured interviewing techniques, and without the use of formal tools.

System Analysis and Assessment:

a. *Functional Resonance Analysis Method (FRAM):* examines the potential sources of variability in a system by mapping relationships between functions. FRAM provides a way to describe outcomes using the idea of resonance arising from the variability of everyday performance.

> Hollnagel, E. FRAM: The Functional Resonance Analysis Method: Modelling Complex Socio-Technical Systems. Ashgate (2012)

b. *Resilience Analysis Grid (RAG):* Checklist of items in a given domain that represent each of the four 'resilience potentials': *monitoring, anticipating, responding, learning*. RAG offers a practical way to identify the capabilities of a system that underpin resilient functioning in 'normal' work.

> Hollnagel, E. (2011). RAG-The resilience analysis grid. *Resilience engineering in practice. A guidebook. Farnham, UK: Ashgate,* 275-296.

c. *Systemic Contributors and Adaptive Diagramming (SCAD):* a tool for visualizing and analyzing adaptive capacity in a system. SCAD traces adaptive patterns that originate in everyday (routine) functioning, to their role during critical (nonroutine) events, such as accidents. Therefore, SCAD demonstrates the underpinnings of resilient functioning in the system across a range of situations.

> Reynolds, M. E., Rayo, M. F., & Woods, D. D. Proactive Systemic Contributors and Adaptations Diagramming (SCAD-P): A Lightweight Tool Delivering Heavyweight Systems-level Insights.

d. *Resiliencer:* Application to visualize the relative operational state vis-à-vis its system boundaries, i.e. the boundaries of performance, workload, and safety. This type of visualization can help identify the trade-offs and inter-relationships between multiple objectives of a system, and where the system is operating relative to these boundaries. The boundary concepts are derived from the work of Rasmussen (1997) and Cook and Rasmussen (2005).

> Siegel, A. W., & Schraagen, J. M. C. (2017). Beyond procedures: Team reflection in a rail control centre to enhance resilience. Safety science, 91, 181-191.

e. *ADAPTER:* A questionnaire based on the four essential capabilities (or potentials) of resilience (Hollnagel, 2011) and expanded with more relation-oriented abilities of leadership and cooperation. The questionnaire can be used to drive discussion among teams around how to better enable key capabilities for resilient functioning.

> van der Beek, D., & Schraagen, J. M. (2015). ADAPTER: Analysing and developing adaptability and performance in teams to enhance resilience. Reliability engineering & system safety, 141, 33-44.

f. *Strategies Framework for Analyzing Adaptations; Variety Space Diagram:* The strategies framework is used to analyze adaptations in everyday situations in which systems are working near the margins of safety. The variety space diagram is used to represent system variability, disturbances, and constraints that affect performance. The strategies are represented within the variety space diagram along multiple continua: regular-to-exceptional disturbances, basic-to-extended control actions, and sharp-end to blunt-end of the system.

> Rankin, A., Lundberg, J., Woltjer, R., Rollenhagen, C., & Hollnagel, E. (2014). Resilience in everyday operations: a framework for analyzing adaptations in high-risk work. Journal of Cognitive Engineering and Decision Making, 8(1), 78-97.

g. *Resilience based early warning indicator (REWI)* is a method for the development of early warning indicators based on resilience and Resilience Engineering. This method consists of three main parts. The first part is a set of contributing success factors being attributes of resilience, the second part is general issues for each of the contributing success factors ensuring that the goal of each contributing success factor is fulfilled, and the third part is the indicators established for each general issue, i.e., the way of measuring the general issues. This research has shown that it is possible to develop 'an indicator system' based on resilience engineering theory from which early warning indicators can be established.

> Øien, K., Massaiu, S., Tinmannsvik, R. K., & Størseth, F. (2010, June). Development of early warning indicators based on resilience engineering. In Submitted to PSAM10, International Probabilistic Safety Assessment and Management Conference (pp. 7-11).

h. *Games for Resilience-based Early Warning Indicator (GREWI):* A serious-games approach of data gathering, based on the REWI method (above).

> Patriarca, R., Falegnami, A., De Nicola, A., Villani, M. L., & Paltrinieri, N. (2019). Serious games for industrial safety: An approach for developing resilience early warning indicators. Safety science, 118, 316-331.

i. *Resilience Mapping Framework (RMF)*: The RMF can be used to identify the four resilience potentials, monitoring, anticipating, responding and learning, at each of five system-levels: the individual, the team, the unit/department, the hospital, and the healthcare network and industry at large. This mapping can be done for specific issues, to identify the relationships between system-levels and opportunities to synergize and better enable resilient capabilities.

> Hegde, S., Hettinger, A. Z., Fairbanks, R. J., Wreathall, J., Krevat, S. A., & Bisantz, A. M. (2020). Knowledge Elicitation to Understand Resilience: A Method and Findings From a Health Care Case Study. *Journal of Cognitive Engineering and Decision Making*, *14*(1), 75-95.

j. *Fuzzy cognitive maps (FCMs):* FCM, originally developed by Kosko et al. (1986), has been used as a way to mathematically evaluate relationships between key resilience concepts identified in a system. The outcome is a list of concepts and capabilities weighted according to their role in enabling resilient operations in a system.

Azadeh, A., Salehi, V., Arvan, M., & Dolatkhah, M. (2014). Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: A petrochemical plant. *Safety Science*, *68*, 99-107.

k. *Q4-Balance Framework* to analyze economy-safety trade-offs. Plotting the sets of metrics used by an organization in the four-quadrant visualization can be used to identify misalignments, overlap and false diversity. It results in a visualization of the set of metrics an organization uses and where these conflict or reinforce each other. The framework also provides a way to assess an organization's safety energy as a kind of analysis of an organization's capability to be proactive about safety.

Woods, D. D., Branlat, M., Herrera, I., & Woltjer, R. (2015). Where is the organization looking in order to be proactive about safety? A framework for revealing whether it is mostly looking back, also looking forward or simply looking away. *Journal of Contingencies and Crisis Management*, *23*(2), 97-105.

Conceptual Descriptions

In addition to tools, the following are some of the concepts that have been highly influential in the RE literature. In fact, several tools described above, are based on one or more of these concepts.

a. *Work as Done (WAD) vs. Work as Imagined (WAI):* WAD, as distinct from WAI, represents the variable and complex nature of work in everyday situations. The notion of WAD being different from WAI underscores the importance of studying adaptations and system-properties across the all types of situations, from the routine or 'normal' work, to critical incidents.

b. *Four capabilities of resilience: monitoring, anticipating, responding, learning:* Hollnagel defines four capabilities (or potentials) that typically characterize resilience. These definitions are helpful in identifying how they are instantiated in a system. Tools such as the RAG, A

c. *Four Concepts of Resilience:* Resilience as: Robustness, Rebound, Sustained Adaptability, and Graceful Extensibility. Woods offers four definitions of resilience that are helpful in clarifying, both the similarities, and uniqueness of resilience as viewed in RE.

Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering & System Safety*, *141*, 5-9.

d. *Safety-II and Safety-I:* Safety-II challenges the traditional paradigm, Safety-I, which seeks to improve safety by focusing on reducing errors and sources of harm, by arguing that it's important to also understand how things go well in everyday work. By identifying how safety is 'created' in everyday situations, e.g. through adaptive capacity, a system can focus on better enabling the underlying capabilities.

e. Dynamic Safety Model: Based on Rasmussen's dynamic model of risk and safety, the model looks at performance within an enveloped defined by boundaries relating to unacceptable workload, economic failure, and acceptable performance. The model can be used to represent the dynamic interplay between these boundaries in terms of their effect on the operating point. Particularly, implications for safety emerge near the boundary of performance due to competing pressures from the boundaries.

Cook, R., & Rasmussen, J. (2005). "Going solid": a model of system dynamics and consequences for patient safety. *BMJ Quality & Safety*, *14*(2), 130-134.

f. *Fractal nature of resilience:* Resilience manifests at multiple levels of scale – macro (societal), meso (organizational), micro (individual), and cross scale. The meso-level is considered as a bridge to create synergy between the macro and the micro.

Bergström, J., & Dekker, S. W. (2014). Bridging the macro and the micro by considering the meso: reflections on the fractal nature of resilience. *Ecology and Society*, *19*(4).