The Resilience Analysis Matrix (RAM): Visualizing functional dependencies in complex socio-technical systems

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Abstract. RAM is a method for visualization to facilitate analysis of functional dependencies in complex socio-technical systems. The RAM facilitates the description of instantiations (as in FRAM) to model system behaviour in for example different situational circumstances or to model "work as planned vs. work as actually done". Instantiations can be traced through following a coloured line. Thereby the RAM can be used for retrospective (reconstructing the actual instantiations of an event) as well as prospective (possible instantiations in future behaviour of the system) analysis. Resilience characteristics (see e.g. Woods, 2006) can be analysed with a focus on functions and with a focus on paths/instantiations. Two cases are described to illustrate the points outlined above: a) The Swedish civil crisis response missions to the Asian Tsunami of 2004 and the Israel-Lebanon war of 2006 b) Attempted take-off from wrong runway accident of Comair Flight 5191, 2006.

1 INTRODUCTION

It is hard to visualize complexity without the visualization becoming overly complicated, thereby hiding the patterns, interactions, and emerging properties that the analysis set out to discover in the first place. A good visualization of functional dependencies in socio-technical systems should not merely illustrate complexity – it should provide an overview of analytical findings and facilitate the discovery of interdependencies of functions.

There are numerous analysis methods for complex systems available that also provide visual presentation and analysis techniques. Among these methods are Cognitive Work Analysis (Vicente, 1999), AcciMap (Svedung & Rasmussen, 2002), system dynamics (e.g. Senge, 1990), and various enterprise architecture frameworks (e.g. Johnson & Ekstedt, 2007). Application of the Functional Resonance Analysis Method (FRAM; Hollnagel, 2012) is done textually but invites for the visualization of analysis results in a loosely-defined manner, e.g. through illustrating instantiations.

The analysis of functional interdependencies and emergent (systemic) phenomena is a central capability of several of these analysis methods. Graphical representations of functional interdependencies and emergent phenomena generated by these methods suffer to varying degrees from difficulties to (1) facilitate the discovery of patterns, emergent properties, and interdependencies, or (2) communicate analytical findings. Nevertheless (and with varying success) both of these purposes are commonly pursued by analysts and scientists, likely because the representation of a problem affects its understanding and solution (e.g., Simon, 1996). Moreover, methods and visualization techniques that aim to aid in the analysis and communication of various systemic properties identified in resilient systems (e.g., buffering capacity, margin, flexibility, tolerance, and cross-scale interactions from Woods, 2006) are rare (although methods such as FRAM seem to be suitable for this purpose, see Woltjer, 2008). The present paper describes a method that aims to reduce these gaps.

2 THE RESILIENCE ANALYSIS MATRIX (RAM)

The purpose of the Resilience Analysis Matrix (RAM) that is proposed in this paper is to facilitate analysis of resilience and safety in complex systems. In RAM, we combine the matrix as a core organizing principle with the Matrix theory of graphics (Bertin, 2001) and basic information design principles (e.g. Tufte, 1990). A matrix is the core organizing principle used in frameworks such as the Design Structure Matrix method (Steward, 1981). The main advantage is that a matrix can present a fully connected function network – with every function being connected to every other function through both input and output – without becoming overloaded. In contrast, a visualization technique that connects functions only through lines quickly becomes overloaded when there are many connections between functions. A line-based technique may also give an illusion of complexity where none exists – comparable to how a chain if dropped on the floor may become entangled, in a complicated way, but still be a linearly connected chain of links.

We present an overview of RAM in Fig. 1 and two RAM examples (Fig. 2 and Fig. 3). Above the lower red dividing line, there is a matrix of functions (Fig. 1 to the left). Each function is presented both in a row, and in a column, with function output on the diagonal. On each row, inputs from (potentially all) other functions can be read. In each column, the output from a particular function to (potentially all) other functions, can be read. This means that even if all functions were connected to each other through input and output, the matrix can still be read, without clutter. Functions that do not have any inputs (that were not analysed further), are considered to be background functions. Those are placed at the top, above a red dividing line to differentiate them with other functions. They are placed at the top since they, in the analysis, will only affect functions below, and will not be affected by functions below.

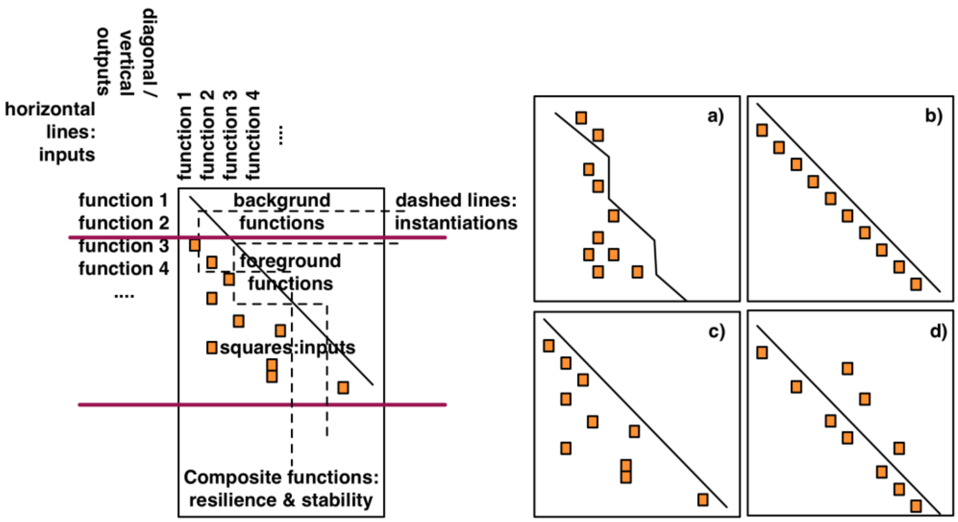

Fig. 1. Resilience Analysis Matrix: General layout and visual analysis patterns.

In RAM, functions should be ordered following functional dependencies. As far as possible, functions should be placed below all functions that they receive inputs from. If there are no feedback loops in the analysis, then there will be no items above the diagonal. A visual inspection immediately reveals this to be the case in examples b and c (Fig. 1). This also means that all feedback loops will be visible above the diagonal, making them stand out in a brief visual inspection (examples a and d, Fig. 1).

RAM can be used with anything from plain input-output markings between functions, to textual descriptions, to use of for example SADT/IDEF0 notation, to FRAM notation. For this analysis, we have used the notation of different inputs from the FRAM method combined with textual descriptions: I) Input that triggers execution of the function, R) Resources that must be available during the execution of the function, P) Prerequisite functions that should be finished before the function starts, T) Time, C) Control input to the function. There is no need for a specific output symbol in RAM, since columns in the matrix represent outputs.

Instantiations (sets of couplings among functions for specified time intervals; Herrera & Woltjer, 2010; Hollnagel, 2012) of the function network are represented by lines drawn on top of the function network. The lines are created by drawing a line through all functions that are involved in an instantiation of the function network. This makes it possible to analyse upstream and downstream interactions for specific instantiations. By following the lines, the analyst can moreover compare instantiations. Differences and similarities between instantiations can easily be seen through visual inspection (see Fig. 2 and Fig. 3). As the next example (Fig. 2) will show, it can also reveal how instantiations may affect subsequent instantiations of the network.

Below the lower dividing line, an analysis of instantiations can be written, facilitating a detailed comparison between the different instantiations. For each function that is activated, the effect (if any) on the outcome is written as an output in its respective column. This both highlights differences between instantiations with regard to what functions are activated, and with regard to what effect or non-effect the activation has.

3 APPLICATION

3.1 Case 1: Resilience and Vulnerability in Crisis Response

Fig. 2 is part of the function network for adaptation of crisis response in the Swedish Civil Response of the Asian Tsunami of 2004 and the Israel-Lebanon War of 2006 (see Lundberg & Rankin, 2013). Over the top dividing line, two background functions are described. Both functions output “positive attitudes” (to taking improvised roles), an important pre-requisite for self-assigning and taking improvised roles.

Four instantiations of the function network are visualized in Fig. 2 as coloured lines. They were derived from stories presented by crisis response personnel describing their experiences (see Lundberg & Rankin, 2013).

Looking at the lines going through the matrix, it is immediately clear from a visual inspection that there are minor differences in paths between the orange and brownish lines. To inspect the significance of the differences, the analyst may follow both lines and identify functions that are activated in one instantiation but not in the other. In this case, the difference lies in the execution of the “survey competences” function. The output from that function is “more optimal role assignments”. This is also reflected in the summary rows for both instantiations below the lower dividing lines. In the summary row, the “more optimal role assignments” are labelled as potentially increasing resilience in terms of increased margin of operations.

Looking the “survey competences” row we see that this function may be affected by a feedback loop (there are items to the right of the diagonal), represented by a red “R” in the network, which represents a resource necessary to carry out the function (the manager). The red “R” is placed in the “manager takes improvised role” column, identifying it is as the function that may cause this situation. Looking in that column, the analyst can see that “green line” instantiations will execute that function. The analysis thus reveals interactions between instantiations. In terms of resilience, it is represented in the row for the “green line” as “inflexibility by disabling role survey and manager assignments.”

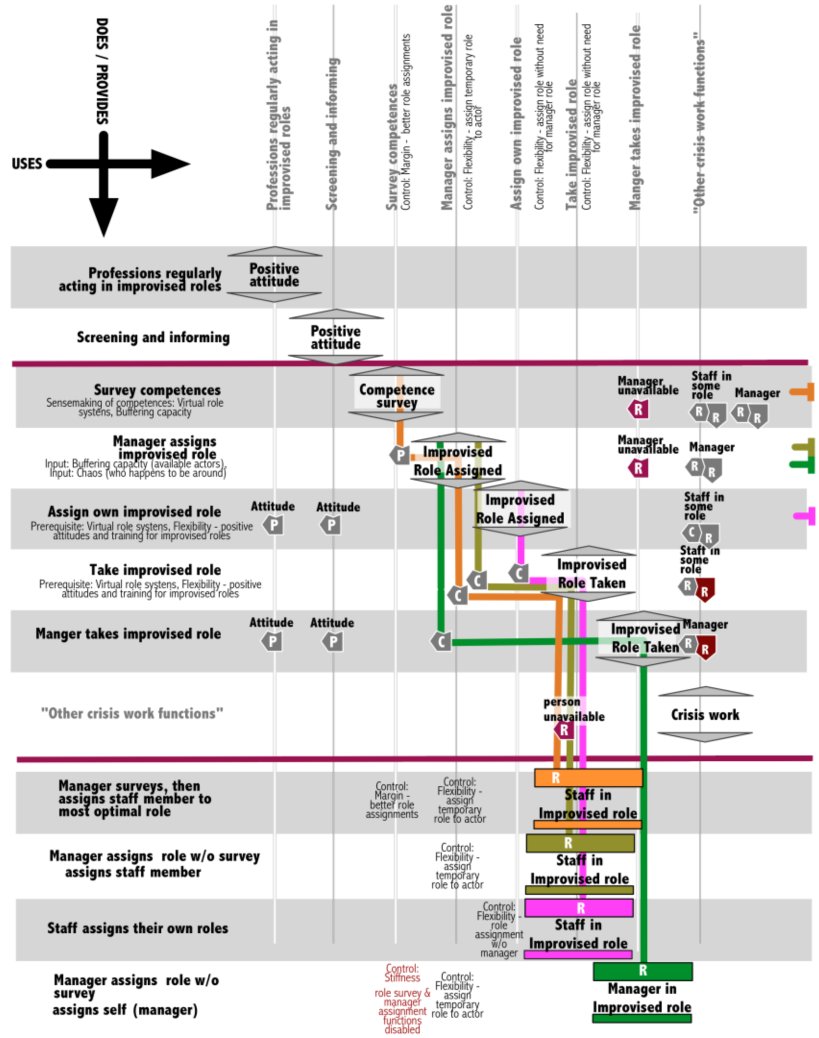

Fig. 2. Resilience Analysis Matrix: Swedish Civil Response of the Asian Tsunami of 2004 and the Israel-Lebanon War of 2006

3.2 Case 2: Performance Variability in an Aviation Accident

Fig. 3 visualises an excerpt from a FRAM analysis (Hollnagel et al., 2008) of the attempted takeoff from wrong runway accident of Comair Flight 5191, (NTSB, 2007). This example shows that RAM can be used to analyse traditional threats to stability as well as analyses of resilience.

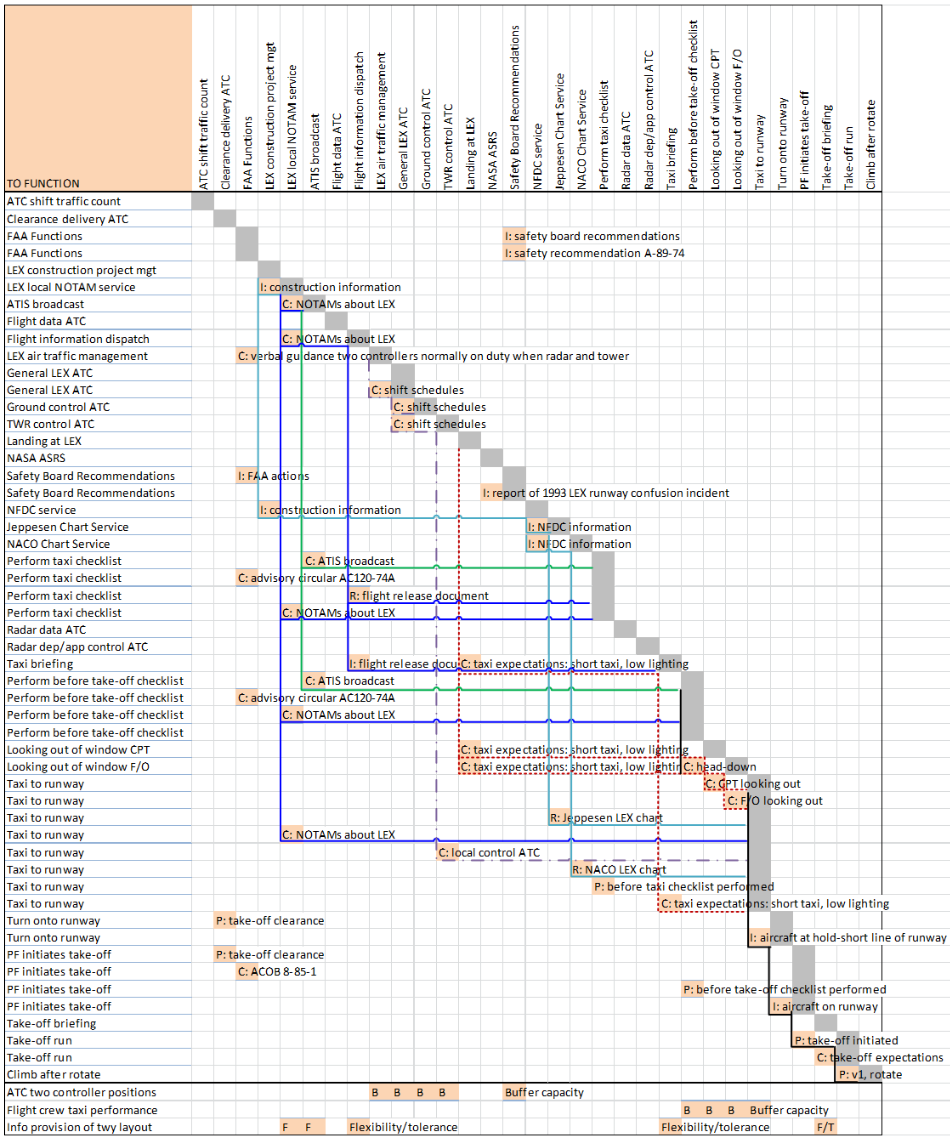

Fig. 3. Resilience Analysis Matrix: The Lexington accident of 2006.

In contrast to Fig. 2, in Fig. 3, each row illustrates input from one function. This means that with input from several different functions, the input will cover several rows, potentially resulting in a imbalanced jagged line (Fig. 1a). The jagged line in this case (Fig. 3) represents the “Taxi to runway” function, which is immediately apparent from a brief visual inspection. The appearance of a “cliff” in the diagonal may indicate that the function is analysed in a too abstract level, implying that the analysis should be increased in granularity and “broken down” into several sub-functions. The RAM thus serves as a suitability check on the granularity of the analysis. Experience with the RAM moreover shows that it serves as a completeness and consistency check on functional models, as the matrix visualises potential couplings.

The analysis shows that roughly the same functions were performed in both the instantiation of performance as planned and the one of performance as actually done. The figure focuses on tracing the effect of combined performance variability by sketching trajectories through the functional network.

The solid coloured lines illustrate the effects of project management (turquois) information about taxiways being reconstructed and unavailable, having effects on NOTAM (blue) and ATIS (green) services, and production of charts (turquois ctd.), affecting checklists and briefings, eventually coming together (black) into the turning onto another runway than intended. The dashed (red) line illustrates part of the trajectory where landing at LEX the day(s) before built up expectations of a short taxi and low lighting levels that affected several functions such as briefing, taxiing, turning onto the runway and the take-off run. The dashed-dotted line (purple) illustrates the effects of a blunt-end ATC management function that affects one position of ATC being open and the controller being busy with other tasks. These trajectories, too, eventually come together (black line) into the turning onto the runway. The RAM thus visualises the effects of contributing factors.

Below the solid line several resilient system characteristics (Woods, 2006) are illustrated. These were intended but not realised in this instantiation, making function performance brittle. Buffering capacity is attempted to be established through several functions together, establishing two ATC positions during TWR/radar service. Similar buffering capacity would be available when both pilots can taxi looking head-up. Flexibility of adapting to changed taxiway construction circumstances and tolerance for conflicting information (e.g., charts, NOTAM) is shown in the third row. The RAM can thus visualise resilience characteristics of the functional system (actual or as intended).

4 CONCLUSIONS

RAM fills a need for visualizing complex systems and their dynamics. RAM overcomes some of the difficulties in current methods such as (1) facilitating the visual discovery of patterns and functional interdependencies, (2) providing an overview of analytical findings of complex systems analyses, (3) interdependencies between instantiations, such as intended vs. actual performance and actual performance over time, and (4) visually organising emergent properties of resilient and brittle systems. RAM is intended to be used by analysts in academia and industry to add a visual analysis approach to other established methods, for both retrospective and prospective analysis. Future research includes evaluating the benefits of using a dedicated tool, and evaluating the communicative power of the visualisations with industry.

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REFERENCES

Bertin, J. (2001). The Matrix Theory of Graphics. *Information Design Journal, 10*(1), 5-19.

Herrera, I. A., & Woltjer, R. (2010). Comparing a multi-linear (STEP) and systemic (FRAM) method for accident analysis. *Reliability Engineering & System Safety, 95*(12), 1269–1275.

Hollnagel, E. (2012). *FRAM: The Functional Resonance Analysis Method - Modelling Complex Socio-technical Systems*. Aldershot, UK: Ashgate.

Hollnagel, E., Pruchnicki, S., Woltjer, R., & Etcher, S. (2008). Analysis of Comair flight 5191 with the Functional Resonance Accident Model. *Proceedings of the 8th Int. Symp. of the Australian Aviation Psychology Association*. Sydney, Australia.

Johnson, P., & Ekstedt, M. (2007). *Enterprise Architecture: Models and analyses for information systems decision making*. Lund, Sweden: Studentlitteratur.

Lundberg, J., & Rankin, A. (2013). Resilience and vulnerability of small flexible crisis response teams: implications for training and preparation. *Cognition, Technology & Work*, DOI:10.1007/s10111-013-0253-z.

NTSB. (2007). *Attempted takeoff from wrong runway, Comair Flight 5191, Bombardier CL-600-2B19, N431CA, Lexington, Kentucky, August 27, 2006* (NTSB/AAR-07/05).

Senge, P. M. (1990). *The fifth discipline - the art and practice of the learning organization*. New York: Doubleday/Currency.

Simon, H. A. (1996). *The sciences of the artificial* (3rd ed.). Cambridge, MA: MIT Press.

Steward, D. V. (1981). The design structure system: A method for managing the design of complex systems. *IEEE Transactions on Engineering Management, 28*(3), 71-74.

Svedung, I., & Rasmussen, J. (2002). Graphic representation of accident scenarios: mapping system structure and the causation of accidents. *Safety Science, 40*, 397–417.

Tufte, E. R. (1990) Envisioning Information. Cheshire, Conn.: Graphics Press.

Vicente, K. J. (1999). *Cognitive Work Analysis: Towards Safe, Productive, and Healthy Computer-Based Work*. Mahwah, NJ: Lawrence Erlbaum Associates.

Woltjer, R. (2008). Resilience Assessment Based on Models of Functional Resonance. *Proceedings of the 3rd Resilience Engineering Symposium*. Sophia-Antipolis, France: MINES ParisTech.

Woods, D. D. (2006). Essential characteristics of resilience. In E. Hollnagel, D. D. Woods, & N. Leveson (Eds.), *Resilience engineering: Concepts and precepts* (pp. 21–34). Aldershot, UK: Ashgate.