FRAM and STAMP: New Avenue for Risk Analysis in Manufacturing in the Era of Industry 4.0

Alimeh MOFIDI NAEINI, Sylvie NADEAU

Department of Mechanical Engineering, École de technologie supérieure Montréal, Québec, Canada

Abstract. Manufacturing in the context of industry 4.0 has become increasingly complex. As the complexity of these systems increases, so to will the potential for emerging hazards. Consequently, finding an appropriate approach to identify, measure and assess new and emerging hazards is imperative to prevent their occurrence or lessen their effects on the human, organizational, and technical scales. FRAM and STAMP applications are two known methods for analyzing risks in complex systems. This study conducts a critical review of the literature on FRAM and STAMP specifically with regards to their application in the manufacturing sector. For this purpose, scientific databases such as IEEE, Compendex and INSPEC, Science Direct, Google Scholar, and Espace ÉTS were consulted for relevant studies from 2004 to 2020, mostly in English. The search keywords included FRAM, STAMP, STPA, manufacturing, risk, industry, and industry 4.0. The results are presented in two tables including the year of publication, the study's aim and results, the type of analyzed risks, and applied methods. Despite the limited number of studies that have applied FRAM or STAMP in manufacturing, the results show that they are suitable for understanding, explaining, and analyzing complex manufacturing systems. They can offer a different perspective on the analysis of the system. However, to the best of our knowledge, their application in manufacturing in the context of industry 4.0, particularly with regards to the use of wearable technologies in manufacturing, has not yet been studied. The results of this review conclude that the use of FRAM and STAMP in manufacturing could be promising for the analysis of digital manufacturing risks, especially wearable technologies used in manufacturing, a point which needs further consideration in future studies.

Keywords: Risk analysis, manufacturing, FRAM, STAMP

1. Introduction

Over the last decades, the management of industrial plants has become increasingly complex regarding various aspects such as interactions, work automation, process structure, and number of components (Gattola et al. 2018; Melanson & Nadeau 2019). Regarding occupational safety, the increasing complexity of industrial systems could lead to an increase in emerging hazards (Leveson 2011). For decades, the way of thinking and analyzing risks were confined to a certain line of reasoning. However, at the end of the 20th century, things began to change as the need for a new approach able to analyze risks in socio-technical systems became prevalent (Slim & Nadeau 2019). Some of the classical methods were not able to illustrate how the interaction of elements of a system including management, organizational and human parameters could cause an accident (Underwood & Waterson 2013). In addition, the use of classical methods such as Fault Tree Analysis (FTA), Failure Mode Effect and Analysis (FMEA), HAzard and OPerability study (HAZOP) have been said to be error-prone, time-consuming, and tedious (Mahajan et al. 2017). To help countermeasure the shortcomings of classical risk analysis methods (Adriaensen et al. 2019; Badri et al. 2018), the application of new approaches such as Functional Resonance Analysis (FRAM) and System-Theoretic Accident Model and Processes (STAMP) are proposed in this paper for the risk analysis of complex manufacturing systems.

2. Methodology

This paper studies the application of FRAM and STAMP in manufacturing. To obtain studies related to our subject, scientific resources at ÉTS library (IEEE, Compendex & INSPEC, Science Direct, Google Scholar, and Espace ÉTS) from 2004 to 2020, mostly in English, were consulted. The applied keywords were: FRAM, STAMP, STPA, manufacturing, risk, industry, and industry 4.0. The search results were narrowed down first by reviewing the titles and then by studying the abstracts. The selected papers were consulted to extract a comprehensive context, including the year of publication, the study's aim and results, the type of analyzed risks, and applied methods. The findings are presented in two tables that show the application of FRAM and STAMP in manufacturing and explain why FRAM and STAMP are more suited for risk analysis in complex manufacturing.

3. Results

3.1 FRAM

FRAM is a systemic model that describes non-linear relationships and interactions between different functions in the studied system. Introduced in 2004 by Erik Hollnagel, FRAM analyzes normal system activities, considers functional variabilities, and deviations from expected performance. It also considers the variability in performance and studies how these functional variabilities might resonate with one another to create unwanted events (Hollnagel 2004). The application of FRAM for risk analysis in manufacturing is presented in Table 1.

Table 1. *The application of FRAM for risk analysis in manufacturing*

Author(s) & Year	Main Objective	Result	Type of Manufacturing process	Type of risk	Method
(Sekeľová & Lališ 2020)	Using Resilience Assessment Grid (RAG) and FRAM to evaluate changes in the process of producing aircraft's components	FRAM will help the analyst to better clarify the relationships among different functions.	Producing aircraft components	OHS and operational risk	FRAM + Resilience Assessment Grid (RAG)
(Melanson & Nadeau 2019)	Compared application of Failure Mode Effect and Criticality Analysis (FMECA) and FRAM	Manufacturing can use FRAM to have a good insight into their operations as socio-technical systems.	Manufacturing of motor vehicles (chassis assembly)	OHS and emerging risk	FRAM and FMECA

Au-thor(s) & Year	Main Objective	Result	Type of Manu-facturing pro-cess	Type of risk	Method
(Gattola, et al. 2018)	Using FRAM for analysis of safety-related issues in metal manufacturing (Forging process)	Using FRAM helped to identify different activities that can poten-tially resonate within the system and introduce emerging events. Hence, the prediction of the changes' effects on the system is easier.	Forging process	OHS risk	FRAM
(Gholamniaet al. 2018)	Evaluating the OHS risk using FRAM and two classic methods including Failure Modes (FM) and Effects Analysis (EA)	Since FM and EA mostly deal with technical issues and FRAM provides an overall view of the system, using both classical methods (FM and EA) and FRAM can significantly improves the system's safety.	Pressing process in car manufac-turing	OHS risk	FRAM
(Patri-arca, et al. 2017)	Application of a devel-oped FRAM with Monte Carlo simulation in a sin-ter plant	The application of developed FRAM with Monte Carlo simula-tion will provide a more accurate assessment with iterative simula-tion.	Sinter plant	Environ-mental risk	FRAM + Monte Carlo
(Z. Zheng & Tian 2017)	Assessing risks of the manufacturing process in an assembly case study (assembly of the rotor)	Applying the new approach pro-vides a new perspective on risk analysis, a deeper understanding and insights on the interaction and dynamics among different components in a manufacturing system.	Manufacturing (the assembly of a rotor on an ele-vator)	Opera-tional risk (quality of prod-ucts)	FRAM+ Fi-nite State Machine + model checker SPIN
(Z. Zheng et al. 2016)	FRAM was used to refine the operation guidelines and improve production processes by reducing the number of unqualified products	FRAM helped to identify the gap between work as imagined and work as done, and finding de-fects in guidelines to improve manufacturing processes to re-duce manufacturing risks.	The forging of aero-engine tita-nium alloy blades	Opera-tional risk (quality)	FRAM
(Albery et al. 2016)	Evaluation of the use of question sets (in four methods including work as done, work as imag-ined, risk matrix, FRAM approach) that are based on FRAM (Safety II)	Questions inspired by Safety II can encourage stakeholders to look for different sources of vari-ability in the working system. It also provides a more in-depth learning of the system's perfor-mance to manage variability.	Manufacturing site that includes different pro-cesses such as assembly, weld-ing, cutting, etc.	OHS and opera-tional risks	FRAM + safety II

3.2 STAMP

STAMP is a model based on system theory that focuses more on system safety than the prevention of failures. In this method, safety is considered as a control problem rather than a reliability issue. This method tries to find the causes of an accident by specifying the reason for its being controlled ineffectively. The following table (Table 2) shows the application of STAMP in manufacturing.

Table 2. *The application of STAMP for risk analysis in manufacturing*

Author(s) & Year	Main Objective	Result	Type of Manufacturing process	Type of risk	Method
(Pope 2019)	Applying STPA for risk analysis of the reproduction of a widget (an item for which production is too expensive, its components are hazardous and it is made by the government)	Using STPA provides a useful perspective on risk analysis and facilitates risk review.	Manufacturing a widget	Governmental, Operational, Environmental, and OHS risks	STPA
(Sousa et al. 2017)	Application of STAMP and Lean philosophy to eliminate or decrease waste in manufacturing	The combination of STAMP and the Lean approach can help make better decisions, reduction of waste and acquire more in-depth information about the system than Lean philosophy.	Car assembly	Operational risk (risk of making waste)	STAMP + Lean philosophy
(Schmittner et al. 2016)	Application of STAMP-based method for assessing safety and security risks (battery management system)	Although STPA-sec is an appropriate approach for managing risks, using with other methods (ISO 26262) provides a comprehensive assessment.	Automotive vehicle	Security risk	STPA-sec + ISO 26262
(Montes 2016)	Applying STPA to test product development after the design completion to ensure quality and safety.	The developed STPA can provide essential human considerations in controllers and analyze social and organizational factors influence on controllers	Governmental manufacturing	Safety risk, Operational risk	STPA + Refined Controller (RC)
(Martínez 2015)	Comparison of the application of FMEA and STPA on electric power steering in the product development phase	STPA can be applied in product development in the early stages. STPA is insightful in that it is able to discover hazards in the system in comparison to FMEA.	Manufacturing (vehicle manufacturing)	Operational risk	STPA
(Li 2012)	Applying STAMP (STPA) and PFMEA to manage the quality risks in the production of printed circuit sheets.	The comparison of the application of STPA and PFMEA shows that STPA provides a structured analysis of the system controls and identifies more potential hazards.	Manufacturing (medical device sensor assembly)	Quality (operational) risk, Safety risk	STAMP (STPA)

Regarding the results of these studies (Tables 1 and 2), FRAM is proposed to help understand outcomes that are non-causal (emergent) and nonlinear to enable predictability and control (Hollnagel et al. 2014). FRAM can introduce a different perspective (systemic view) in the system analysis process, and help identify variabilities that might be critical for the proper functioning of the system (Slim & Nadeau 2020). Moreover, STAMP provides a better and more in-depth understanding of the system and its hierarchy, an overview of the required controls, also the relationships between system components (Salmon et al. 2012).

In a proposed classification of systems based on manageability and coupling, manufacturing and assembly lines are considered as a system with average coupling and good manageability (Figure 1- quarter number 3) (Hollnagel 2008; Underwood & Waterson 2013). Given the classifications of appropriate methods for analyzing risks (Hollnagel & Speziali 2008), when the tractability (manageability) is lower and the interaction (coupling) is higher, methods including FRAM, STAMP, and to some extent

Cognitive Reliability and Error Analysis Method (CREAM) are better suited for risk analysis (Adriaensen et al. 2019) (Figure 2).

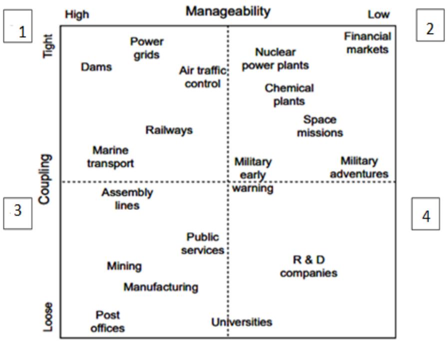

Figure 1. *Classification of systems based on manageability and coupling (Underwood & Waterson 2013); (Hollnagel 2008)*

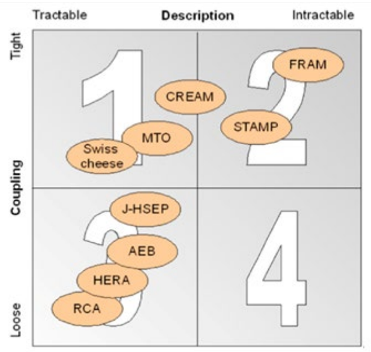

Figure 2. *Characterization of different methods for risk analysis (Adriaensen et al. 2019; Hollnagel & Speziali 2008)*

Considering results of the application of FRAM and STAMP as well as the complexity of the studied manufacturing systems, FRAM and STAMP are considered the most appropriate approach for analyzing risks (Adriaensen et al. 2019; Hollnagel & Speziali 2008). In addition, with the introduction of industry 4.0 to manufacturing, couplings and complexity will consequently increase. Therefore, some changes in the positioning of the manufacturing sectors within the quadrants are to be expected (Adriaensen et al. 2019). The introduction of new technologies can accelerate an increased tightening of couplings (Hollnagel & Speziali 2008) and generate more non-linear and unpredictable system behaviors that are not easy to manage (Pope 2019; Rodríguez & Díaz 2016). Introducing wearables to the manufacturing system as an emerging technology could make the coupling between components tighter and lower the system's manageability. Thus closer to quarter 2, the preferred methods of risk analysis are FRAM and STAMP.

4. Conclusion

Different studies have shown that FRAM and STAMP can provide a systemic view of system analysis. The deployment of new technologies such as wearable technologies in manufacturing systems increases the couplings among components and manageability will decrease. Regarding the characteristics of FRAM and STAMP, they could be considered as promising methods for manufacturing risk analysis in the context of industry 4.0. However, more studies are required to investigate the effect of the deployment of wearable technologies in manufacturing.

5. References

Adriaensen A, Decré W, Pintelon L (2019) Can Complexity-Thinking Methods Contribute to Improving Occupational Safety in Industry 4.0? A Review of Safety Analysis Methods and Their Concepts. Safety, 5(4), 65.

Albery S, Borys D, Tepe S (2016) Advantages for risk assessment: Evaluating learnings from question sets inspired by the FRAM and the risk matrix in a manufacturing environment. Safety science, 89, 180-189.

Badri A, Boudreau-Trudel B, Souissi, A S (2018) Occupational health and safety in the industry 4.0 era: A cause for major concern? Safety Science, 109, 403-411.

Gattola V, Patriarca R, Tomasi G, Tronci M (2018) Functional resonance in industrial operations: A case study in a manufacturing plant. IFAC-PapersOnLine, 51(11), 927-932.

Gholamnia R, Atari S, Matin A (2018) Comparison of failure mode & effect analysis and fanctional resonane in press shop. J Qazvin Uni Med Sci, 22(1), 42-51.

Hollnagel E (2004) Barriers and accident prevention. In: England Publishing Limited: Ashgate.

Hollnagel E (2008) The changing nature of risk. Ergonomics Australia Journal, 22(1-2), 33-46. Retrieved from https://hal-mines-paristech.archives-ouvertes.fr/hal-00508858.

Hollnagel E, Hounsgaard J, Colligan L (2014) FRAM-the Functional Resonance Analysis Method: A Handbook for the Practical Use of the Method: Centre for Quality, Region of Southern Denmark.

Hollnagel E, Speziali J (2008) Study on Developments in Accident Investigation Methods: A Survey of the "State-of-the-Art. SKI Report 2008:50 (Swedish Nuclear Power Inspectorate) - ISSN 1104-1374. Retrieved from https://hal-mines-paristech.archives-ouvertes.fr/hal-00569424

Leveson N (2011) Engineering a safer world: Systems thinking applied to safety: MIT press.

Li T (2012) Systems Theoretic Accident Model and Process application: quality control in medical device manufacturing. Doctoral dissertation, Massachusetts Institute of Technology, Retrieved from http://hdl.handle.net/1721.1/90689.

Mahajan H S, Bradley T, Pasricha S (2017) Application of systems theoretic process analysis to a lane keeping assist system. Reliability Engineering & System Safety, 167, 177-183.

Martínez R S (2015) System theoretic process analysis of electric power steering for automotive applications. Doctoral dissertation, Massachusetts Institute of Technology.

Melanson A, Nadeau S (2019) Resilience engineering for sustainable prevention in the manufacturing sector: A comparative study of two methods of risk analysis. American Journal of Industrial and Business Management, 9(01), 267.

Montes D R (2016) Using STPA to inform developmental product testing. Doctoral dissertation, Massachusetts Institute of Technology.

Patriarca R, Di Gravio G, Costantino F, Tronci M (2017) The Functional Resonance Analysis Method for a systemic risk based environmental auditing in a sinter plant: A semi-quantitative approach. Environmental Impact Assessment Review, 63, 72-86.

Pope G (2019) Risk Management Using Systemic Theoretic Process Analysis (STPA). Retrieved from Lawrence Livermore National Lab (LLNL), Livermore, CA (United States).

Rodríguez M, Díaz I (2016). A systematic and integral hazards analysis technique applied to the process industry. Journal of Loss Prevention in the Process Industries, 43, 721-729.

Salmon P M, Cornelissen M, Trotter M J (2012) Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP. Safety Science, 50(4), 1158-1170.

Schmittner C, Ma Z, Puschner P (2016) Limitation and Improvement of STPA-Sec for Safety and Security Co-analysis, SAFECOMP 2016, Cham.

Sekeľová F, Lališ A (2020) Application of resilience assessment grid in production of aircraft components. MAD-Magazine of Aviation Development, 7(4), 6-11.

Slim H, Nadeau S (2019) A proposal for a predictive performance assessment model in complex sociotechnical systems combining fuzzy logic and the Functional Resonance Analysis Method (FRAM). American Journal of Industrial and Business Management, 9(6), 1345-1375.

Slim H, Nadeau S (2020) A mixed rough sets/fuzzy logic approach for modelling systemic performance variability with FRAM. Sustainability, 12(5), 1918.

Sousa, Marcelo Santiago De, Felipe Martins Torres, Ariosto Bretanha Jorge (2017) Application of STAMP methodology in one complex manufacturing system. International Journal of Industrial and Systems Engineering, vol. 27, no 3, p. 311-339.

Underwood P, Waterson P (2013) Accident analysis models and methods: guidance for safety professionals. Loughborough: Loughborough University, 28.

Zheng Z, Tian J (2017) Application of FRAM to risk assessment in manufacturing process. Paper presented at the 26th European Safety and Reliability Conference, ESREL 2016, September 25, 2016 - September 29, 2016, Glasgow, United Kingdom.

Zheng Z, Tian J, Zhao T (2016) Refining operation guidelines with model-checking-aided FRAM to improve manufacturing processes: a case study for aeroengine blade forging. Cognition, Technology & Work, 18(4), 777-791.

Acknowledgement. The authors would like to thank the National Sciences and Engineering Council of Canada (NSERC) for their support.

Gesellschaft für
Arbeitswissenschaft e.V.

Arbeit HUMAINE gestalten

67. Kongress der
Gesellschaft für Arbeitswissenschaft

Lehrstuhl Wirtschaftspsychologie (WiPs)
Ruhr-Universität Bochum

Institut für Arbeitswissenschaft (IAW)
Ruhr-Universität Bochum

3. - 5. März 2021

GfA-Press

Bericht zum 67. Arbeitswissenschaftlichen Kongress vom 3. - 5. März 2021

Lehrstuhl Wirtschaftspsychologie, Ruhr-Universität Bochum
Institut für Arbeitswissenschaft, Ruhr-Universität Bochum

Herausgegeben von der Gesellschaft für Arbeitswissenschaft e.V.
Dortmund: GfA-Press, 2021
ISBN 978-3-936804-29-4

NE: Gesellschaft für Arbeitswissenschaft: Jahresdokumentation

Als Manuskript zusammengestellt. Diese Jahresdokumentation ist nur in der Geschäftsstelle erhältlich.

Schriftleitung: Matthias Jäger
im Auftrag der Gesellschaft für Arbeitswissenschaft e.V.

Screen design und Umsetzung
© 2021 fröse multimedia, Frank Fröse
office@internetkundenservice.de · www.internetkundenservice.de