Modelling and Optimizing Socio-technical Operations in Healthcare Using the FRAM and Reinforcement Learning

by

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Abstract

This PhD research work is intended to model, analyze, and optimize socio-technical operations in healthcare using a systemic approach and reinforcement learning. An extensive literature review is presented, and the main knowledge gaps related to modelling and optimizing socio-technical operations in healthcare are clearly outlined and addressed in this research work.

Introduction: Hospital to home transition processes of frail older adults include a set of actions for frail people who are discharged from hospital to their home in the community. The transition process exhibits dynamic interactions between technology, humans, organizations, and the environment. The non-linear dependencies among these influential parameters complicate the understanding of the transition process and the mechanism of modelling its operations.

Objectives: The objectives of this research work are (a) To identify the strengths and shortcomings of the FRAM in modelling complex socio-technical systems; (b) To develop a comprehensive model of the hospital-to-home transition process for frail patients; (c) To capture and visualize different characteristics of variability in the transition process; (d) To monitor frail patients' transitions from hospital to home; (e) To identify challenges of the transition process; and (f) To explore functional pathways to identify transition processes with the highest quality of care and services for frail older people.

Methodology: This research work uses the Functional Resonance Analysis Method (FRAM) to study and model the complexity of the transition process. A

complementary tool for the FRAM (DynaFRAM) is also used to characterize functional and system variability in order to identify the challenges of successful transition processes. Additionally, this research employs the reinforcement learning technique to explore the functional transition model generated by the FRAM to investigate a basic method to optimize the transition process for frail people.

Results and discussion: The results of this research work show that FRAM-generated models can serve as a basis in further analyses regarding complexity, safety, and risk management. The results also indicate that the DynaFRAM tool helps monitor patients' hospital-to-home transitions and characterize different types of variability in functional and system outputs. A comprehensive model[1] of the transition process was built using the FRAM. It includes a library of 38 functions classified in five categories. The outcomes of using the DynaFRAM for monitoring patients' transitions revealed functions with significant variability. The variability observed in the outputs of these functions could be challenging as the variability of a function can reinforce the variability of down-stream functions and affect the performance of the entire transition process. Finally, the results of coupling the FRAM to reinforcement learning help evaluate the system performance in terms of accumulated action value achieved by an artificial agent during functional pathways.

Conclusion: In light of the FRAM, the complexity of the transition process can be visualized and understood better. The application of the DynaFRAM helps enhance the situation awareness of frail patients through providing healthcare providers with where a patient is and what they need during the transition process. Coupling the

[1] The transition model is called comprehensive as it includes the perspectives of healthcare professionals, patients, and caregivers. It also involves pre-discharge and post-discharge processes.

FRAM and reinforcement learning would benefit the healthcare system by providing guidance on how to provide the best care to frail patients in the light of various circumstances.

Dedication

To the memories of my mother for countless efforts she put in to carve me …

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I would like to acknowledge with gratitude the guidance provided by my supervisors, Prof. Brian Veitch, Dr. Doug Smith, and Sarah Power. Their enormous research experience and knowledge have brought me to think seriously on the problem I have taken up in this thesis. Also, their diverse interests helped me think over a problem with different perspectives. It has been a pleasure working under their supervision on this PhD research project.

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Chapter 1

Introduction

1.1. Problem statement

The healthcare sector is under tremendous pressure from the competing requirements of increasing efficiency, safety, and economic viability (Hollnagel & Braithwaite, 2019). One of the most significant challenges in healthcare systems is the maintenance of health in old age. The proportion of people aged 65 and older is projected to increase worldwide in the coming decades and the World Health Organization has declared 2020-2030 the “Decade of Healthy Ageing” in response to this demographic shift (World Health Organization, 2015). During the last three decades, the population of people in the age range of 65 years and above has witnessed an increasing trend in Canada (Canadian Frailty Network, 2020). Moreover, life expectancy has increased in developed countries, which has been one of the greatest achievements of public health in the twentieth century (Oeppen & Vaupel, 2004).

As people age, there is a decline in their physical and mental capacity, and the risk of morbidity and frailty increases. Frailty is a reduction in the capability to respond to stressors and an increased vulnerability to adverse outcomes (Fried et al., 2001). It has important implications for the capability to retain independent, high quality living, and carries an increased risk of hospital visits, disability, and death (Heuberger, 2011). Aging intensifies the degree of frailty, making it more likely that illness in seniors will contribute to some degree of functional decline (Ebrahimi et al., 2013; Williams et al., 2009). The vulnerability of frail older adults to unexpected events and their functional decline while being hospitalized heightens the need for developing an inclusive approach to address the issues and needs of frail older adults.

Healthcare, a socio-technical system, exhibits dynamic interactions between technology, humans, organizations, and the environment (Holden et al., 2013). Hospital-to-home transition processes are complex given that multiple human-organizational factors are involved (O'Hara et al., 2020; Robinson et al., 2012). The perceptions of different stakeholders, such as frail patients, caregivers, and healthcare providers, make such transitions more complicated. The fundamental intention of human factors, especially systemic approaches, is to improve the safety of people in complex processes, such as care transitions (Aase & Waring, 2020). To cope with the complexity of transitional processes and to promote successful transitions, the involvement of a variety of health professionals is often required (Nuernberger et al., 2018).

Transitioning patients within and across healthcare facilities, including hospital to home, is recognized as a complex process (Salehi, Hanson, et al., 2021). Frail older adults are at a significant risk during hospital-to-home transition processes, particularly after the discharge process when patients leave the hospital to receive care at home (Li et al., 2014). These transitions are critical and vulnerable points in the provision of health care. Hospital-to-home transitions include both pre- and post-discharge processes and can be challenging for healthcare providers, older adults, and their family caregivers (Isenberg et al., 2021). They are complex, multiple-step processes that require integrated communication and coordination among the patient, their caregivers, the hospital team, and home and community care providers. The transition process is further complicated by the complexities of the health system because care and services are delivered by multiple healthcare providers with various levels of accountability (Salehi, Hanson, et al., 2021). The factors influencing the transition process are shown in Figure 1.1.

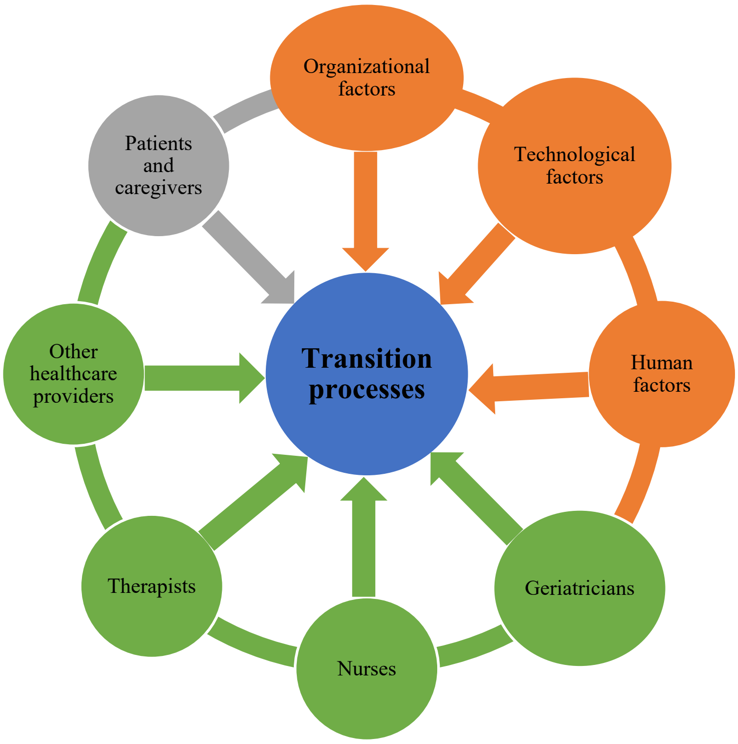

Figure 1.1: Factors influencing hospital-to-home transitions.

When the transition process is not managed well, patients may suffer harm from errors and delays in care and services. Either can result in avoidable hospital readmissions, emergency department visits, and increased healthcare costs. They can also negatively affect frail older patients' experiences (Dhalla et al., 2012). The transition process is recognized as a period of vulnerability for frail older adults due to the requirements for ongoing medical care at hospital and close monitoring at home (Zhou et al., 2021).

Accordingly, the health system strives to improve frail patients' experience in the transition process from hospital to home (Kiran et al., 2020).

The issues regarding the transition process can arise from patient characteristics, healthcare system characteristics, or the interactions between patients and the healthcare system (Dhalla et al., 2012). Thus, there is a clear need to better understand the complexity of and the gaps in these transition processes. A better understanding of the complexity of the constituent elements of the transition process and interactions among them would lead to improving the transition process for older adults.

1.2. Complexity of socio-technical systems

Socio-technical systems are related to the social aspects of people and society and technical aspects of organizations and their processes. Humans and their environments, including technologies and organizations interact with each other in workplaces related to socio-technical systems. Health care is basically a sociotechnical system in which people (healthcare providers, patients, families, and purchasers) have an important role. Many activities are done by means of devices and technologies in healthcare (Carayon, 2006).

Different dimensions of system complexity have been identified (Carayon, 2006; Vicente, 1999). The dimensions and relevant examples in healthcare are presented in Table 1.1, as healthcare systems possess many of the characteristics of system complexity. Healthcare system is composed of many different elements. It involves many different types and categories of workers, patients and their families, and communities. It is comprised of a range of subsystems connected with each other. The subsystems consist of hospitals, community pharmacies, clinics, laboratories, and long-term facilities. Because of the variety of systems and subsystems, there are different goals, values, beliefs, and norms of behavior in healthcare systems (Carayon, 2006).

Table 1.1: Dimensions of system complexity (Carayon, 2006).

Dimensions	Examples in healthcare
Large problem spaces	There are 155,000 codes for diseases and other symptoms.
Social	People centered People driven
Heterogenous perspectives	Different goals, beliefs, values, and behavior norms Different cultures and subcultures
Distributed	Geographical dispersion (e.g., home care)
Dynamic	Changes in medical knowledge and technology
Potentially high hazard	Patient safety and medical errors
Many coupled subsystems	Both tight and loose coupling
Automated	High levels of automation in certain parts of health care (e.g., radiotherapy)
Uncertain data	Imperfect information Patient factors (e.g., impact of treatment on a particular patient)
Mediated interaction with computers	Medical devices and technologies (e.g., endoscopic technologies)
Disturbances	Unanticipated events

1.3. Functional Resonance Analysis Method (FRAM)

A brief description of the Functional Resonance Analysis Method (FRAM) is presented here as it will be fully described in Chapter 2. The FRAM is a method to analyze how work activities are performed. This is done by analyzing work activities to produce a model or representation of how work is done (Hollnagel, 2012). The produced FRAM model can be used for specific types of analysis: to determine how something went wrong (accidents), to look for possible hazards, to check the feasibility of proposed solutions or interventions, or to understand how an activity (or a service) is done. The FRAM is also used for modelling socio-technical systems (Hollnagel, 2012). Even though it is not a risk assessment or an accident analysis method, the model produced by the FRAM can serve as the basis for complexity management, event or accident investigation, safety management, and risk analysis (Salehi, Veitch, et al., 2021).

Function and variability are two important concepts in FRAM analyses. An activity of a sub-system or an entire system is called a function. A set of functions or activities describes how a system works. Each function can be described through six aspects (input, output, precondition, resource, time, and control). The deviations observed in the outputs of a function or in the outcomes of a system is called variability (Hollnagel, 2012).

Output is what is produced after executing a function and can be qualitative or numerical. When a function is executed, the temporary status of the rest of the functions in the FRAM model can be upstream[2] or downstream[3]. An underlying principle of the FRAM is that the output is emergent (Hollnagel, 2012). Emergence means that the outputs result from functions that interact together. That is, there is no linear cause-effect relationship between the output of a function and other aspects. Hence, an input to a function does not "cause" the output. It can start a function. The

[2] Upstream functions are functions that have already been executed and may provide input, precondition, resource, control, or time required for executing the function that is being executed (Hollnagel, 2012).

[3] Downstream functions are functions that follow the function that is being carried out (Hollnagel, 2012).

output of a function depends on the aspects (input, precondition, resource, time, and control), the variability of upstream functions, and the way the function that is being carried out interacts with the upstream functions (Hollnagel, 2012). Therefore, the output of a function in the FRAM modelling is not an under-control variable to be described based on other aspects of the function.

There seem to be similarities between describing the output in the FRAM modelling and the response variable in statistical modelling, such as regression modelling. A dependent response variable could be projected based on some independent (and dependent) variables in the regression modelling. On the other hand, the output of a function in the FRAM modelling can be quantified if there is enough information about the aspects of the function and the variability of upstream functions as the variability of upstream functions can affect the output of the function that is being carried out. There are at least two significant differences between the statistical modelling and the FRAM modelling. First, the FRAM modelling includes many variables compared to the statistical modelling. Second, variables are not under control in the FRAM modelling.

1.4. Overview of hospital to home transitions

Reviewing the literature in the fields of human factors, ergonomics, and healthcare shows that a significant number of studies have been conducted investigating the transition or discharge process of frail patients from hospital to home (Aydon et al., 2018; Barnhart & Carpenter, 2016; Randriambelonoro et al., 2020). Some of the studies regarding the transition process of frail patients that used systemic approaches other than the FRAM are reviewed here. The systemic approaches are Systems Engineering Initiative for Patient Safety (SEIPS), Systems Theoretic Process Analysis (STPA), and Human Factors Analysis and Classification System (HFACS). The application of the systemic approaches is described in the healthcare domain if there is no specific application related to the transition process of frail patients.

Laugaland et al. (2012) conducted a qualitative study for identifying interventions for enhancing patient safety during transitional care of frail patients. The outcomes of the study indicated a number of intervention types, such as organizational interventions, profession oriented interventions, and patient/next of kin oriented interventions. Kianfar et al. (2019) presented a framework of care coordination for chronically ill patients using a comparative method. Interviewing 12 healthcare professionals led to identifying factors influencing care coordination. “Exchanging information about patient transition”, “arranging services and equipment for the patient”, “helping the patient with appointments and transportation”, and “scheduling follow-up to review patient status” were some of the factors that influenced the patient transition.

Williams et al. (2009) investigated emergency department-to-home transitions of older adults using the SEIPS 2.0 model. The SEIPS model was applied for analyzing processes that occur across multiple work systems. The results showed the SEIPS model is able to identify and model work system barriers even though the model misses some technological, human, and organizational factors in the system. It is also capable of providing a basis for evaluating the patient transition across system boundaries. Aase & Waring (2020) conducted a qualitative study to establish a framework to investigate safety and quality in care transitions. The results of the study showed that some components, such as communicative, cultural, collaborative, patient-based, and competency-based factors affect the safety and quality of the care transitions. Kaya (2021) used the STPA to evaluate risks in the sepsis treatment process. The outcomes of the study showed that the STPA does not facilitate an in-depth understanding of the functionality of a system, while it provides a framework for more comprehensive risk assessment. Another deficiency of the STPA is that it does not cover performance variability in daily operations. Bickley and Torgler (2021) applied the HFACS to the public health sector to prevent incidents during the COVID-19. It is a systemic approach to incident and accident investigations. The results of the study showed that the HFACS helps mitigate potential errors at different levels in the public health system. Despite the advantages of the approach in mitigating accidents and incidents, it does not investigate the ways in which a system can succeed. In other words, it does not show all possible (successful and unsuccessful) ways a system can function.

A review of the literature shows some studies employed the FRAM to investigate the transition process of frail patients. The studies are described and discussed here. Laugaland et al. (2014) used the FRAM to identify functions, variability, and performance shaping factors in the discharge process of 20 frail older hospitalized patients. The study outcomes indicated that the FRAM is capable of providing a detailed understanding of the discharge process, and of recognizing the sources of performance variability influenced by various factors. Recently, Buikstra et al. (2020) employed the FRAM for analyzing the discharge process of frail patients and for understanding variability in everyday operations of the discharge process. The results of the study highlighted the role of the FRAM in modeling complex processes and addressing issues associated with performance adjustments in everyday activities of frail older adults. The results of the FRAM also showed that changes based on the aggregation of variability could decrease the probability of undesired outcomes for frail older patients. O'Hara et al. (2020) also applied the FRAM to model transitional care using different stakeholder perspectives. The FRAM model was used to expand a theory of change for guiding intervention development. The study identified 27 functions with related interdependencies. The results of the study showed that concentrating on activities such as maintaining patient mobility and reinforcing the understanding of medication and conditions help to enhance outcomes for frail patients after discharge.

1.5. Why FRAM?

This section explains the reasons behind choosing the FRAM to meet (some of) the objectives of this PhD research work. A rereview of the application of the FRAM and other systemic approaches (SEIPS, STPA, and HFACS) to healthcare-related studies was presented in Section 1.4.

A synthesis of the studies that used systemic approaches other than the FRAM indicated that there is a lack of a detailed model of the transition process of frail patients. The outcomes of the study conducted by Rennke et al. (2013) confirm that the transition model built by other approaches do not provide enough details regarding the transition process of frail older adults. Additionally, the methods and models presented in the studies suffer from investigating non-linear relationships between different elements of the transition process except the STPA. The inherent variability in everyday activities that can potentially lead to undesired outcomes was not investigated in the studies. Several studies emphasized these deficiencies (Kaya et al., 2019; Laugaland et al., 2014; O'Hara et al., 2020; Salehi, Hanson, et al., 2021). As the FRAM is able to provide a detailed model of any process, specify the dependencies between functions, and characterize the variability of daily operations, this PhD research work has adopted this method to model the transition process of frail older adults as a basis for further analyses. The FRAM modelling improves tractability of processes in socio-technical systems, such as healthcare and builds a functional understanding of healthcare processes. A balanced understanding formed from "all stakeholders" is another important advantage of using the FRAM. It should be noted that the suitability of the FRAM in modelling complex socio-technical systems will be fully discussed in Chapter 2.

1.6. Current state of knowledge and gaps

A considerable number of studies have employed the FRAM in different domains for different purposes (Patriarca et al., 2020; Salehi, Veitch, et al., 2021). Therefore, there is a clear need to conduct a review article of the published studies associated with the application of FRAM to categorize its aims, domains, possible deficiencies, and other ambiguous points. Such a review reveals the capability of the FRAM in modeling complex socio-technical systems and monitoring what happens in their operations. The outcomes of such a review can be helpful for academics, scholars, and practitioners who study, research, and work in the field of complex socio-technical systems. They can enhance their knowledge about the developments and practical applications of the FRAM.

A review of the existing studies (presented in Section 1.4) associated with the transition process of frail older adults using the FRAM and other systemic approaches reveals the following weaknesses:

i. The existing hospital-to-home transition models are not comprehensively constructed to include pre-discharge and post-discharge processes.
ii. Previous studies did not characterize and visualize different characteristics (qualitative, quantitative, and temporal) of variability in complex healthcare operations.
iii. Previous studies did not monitor the transition process of frail older adults.
iv. Previous studies did not investigate the challenges of the transition process.
v. Previous studies did not explore functional pathways to identify transition processes with the highest quality of care and services for frail older people.

1.7. Research objectives

The objectives of this PhD thesis are presented in detail in Table 1.2. This thesis selects two methods to meet the objectives: functional resonance analysis method (FRAM) and reinforcement learning. A dynamic version of the FRAM, which is a complementary tool for the FRAM is also used in this research work. The FRAM is used to represent a functional model of the complexity of interactions between different elements/functions of the hospital-to-home transition process. A synthesis of the FRAM related studies revealed that no studies to date have fully modelled, investigated, and monitored issues related to both pre-discharge and post-discharge processes for frail patients using the FRAM (Table 1.3). This study also aims to monitor the transition process of frail patients and to identify challenges they face during the transition process. As shown in Table 1.3, the current study incorporated the perspectives of both healthcare providers and patients/caregivers in the model of the transition process. Another unique characteristic of this study is the use of a complementary tool for the FRAM to monitor patients' transitions between admission and (possible) readmission processes. It helps identify challenges affecting the transition process, which is another unique aim of this study. Moreover, the current research aims to explore functional pathways related to the transition processes using an artificial agent through coupling the FRAM to a reinforcement learning approach. This coupling introduces a basic method to provide guidance on how to provide the best care to frail older patients. In summary, this research aims to provide a basis for healthcare professionals on how to promote successful hospital-to-home transitions for frail older adults. In this regard, this research is conducted to meet the following objectives:

(a) To identify the strengths and shortcomings of the FRAM in modelling complex socio-technical systems through reviewing the literature.
(b) To develop a comprehensive model of the hospital-to-home transition process for frail patients with the FRAM.
(c) To capture and visualize different characteristics of variability in the transition process with a dynamic version of the FRAM.
(d) To monitor frail patients' transitions from hospital to home with the dynamic version of the FRAM.
(e) To identify challenges of the transition process based on performance variability regarding functional outputs.

(f) To couple the FRAM and reinforcement learning technique to explore functional pathways using an artificial agent to identify transition processes with the highest quality of care and services for frail older people.

1.8. Thesis organization

The thesis is written in manuscript style. Four articles have evolved during this research that appear as Chapters 2, 3, 4, 5, respectively (Figure 1.2). Table 1.2 presents these articles in detail to elaborate on the connection with the overall objectives of the thesis.

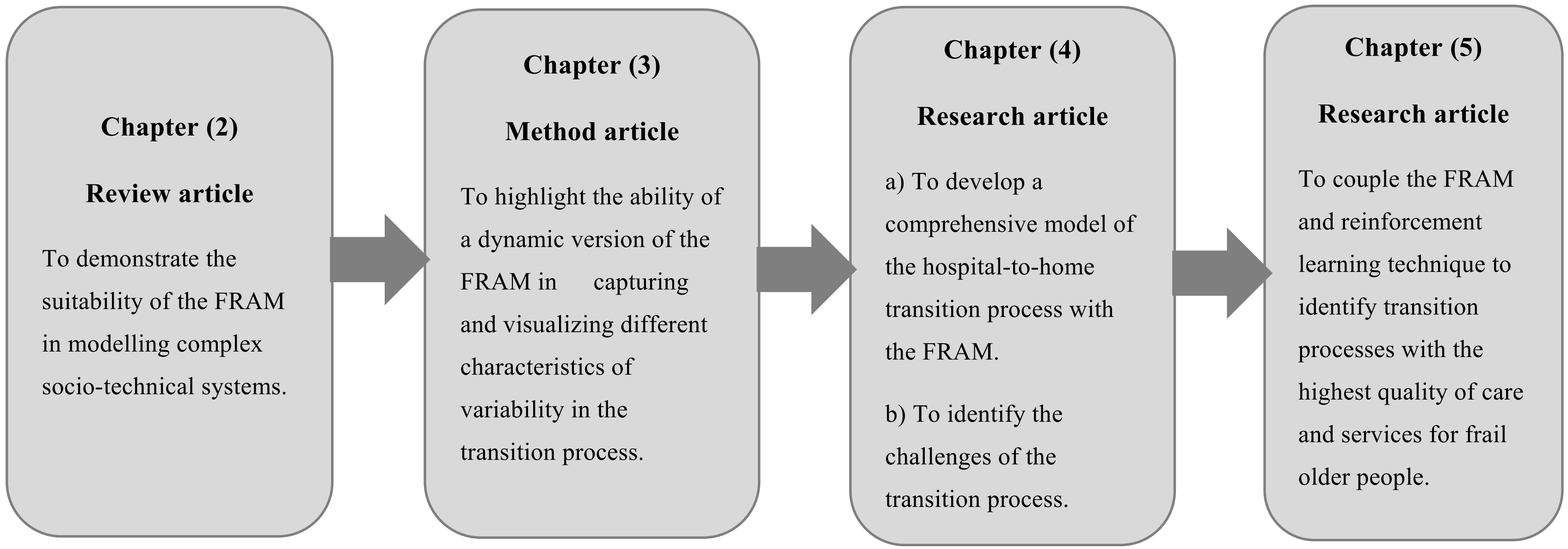

Figure 1.2: The four manuscripts constituting this PhD thesis.

Table 1.2: Articles and their connection to the overall research objectives of the thesis.

Article titles	Research objectives	Associated tasks
Chapter 2: Modelling complex socio-technical systems using the FRAM: A literature review.	• To understand the suitability of the FRAM in modelling socio-technical systems. • To identify the analytical and computational shortcomings of the FRAM in analyzing socio-technical systems.	• To show the importance of the FRAM in understanding the complexity of socio-technical systems. • Identify important literature. • Identify important domains and contexts that applied the FRAM. • Identify appropriate data collection approaches in practice. • Identify the deficiencies of the FRAM.
Chapter 3: A dynamic version of the FRAM for capturing variability in complex operations	• To introduce and test a dynamic version of the FRAM to address the variability-related deficiencies of the FRAM related tools.	• To visualize functional outputs. • To characterize the variability observed in functional outputs. • To visualize the outcome of the entire system in the transition process. • To characterize the variability observed in the outcomes of the entire system. • To monitor the transition process regarding frail patients.

Chapter 4: Modeling and analyzing hospital to home transition processes of frail older adults using the functional resonance analysis method (FRAM)	• To model hospital to home transition processes of frail older adults by the FRAM. • To monitor patients' transition processes. • To identify the challenges of the transition process.	• To describe the multi-phase, multi-sited and mixed methods design of the data collection process. • To identify activities/functions involved in daily operations regarding the transition process of frail older people. • To classify identified functions of the transition process into different categories. • To build a functional model of daily operations regarding the transition process of frail older people using the FRAM. • To monitor the transition process for each patient using a dynamic version of the FRAM (DynaFRAM). • To identify the challenges of the transition process using the variability observed in the outputs of main functions.

Chapter 5: A reinforcement learning development of the FRAM for functional reward-based assessments of complex systems performance	• To introduce a functional reinforcement learning approach to exploring functional pathways related to the transition processes using an artificial agent to provide guidance on how to provide the best care to frail patients.	• To describe the initial requirements of coupling the FRAM and reinforcement learning. • To identify starting and terminal functions. • To define a set of probabilities for probabilistic connections. • To define a set of reward values for each action taken by the agent. • To design testing scenarios. • To examine the functionality of the functional reinforcement learning approach using the testing scenarios. • To do sensitivity analysis to determine the most important functions involved in the discharge process of frail older people.

1.9. Contribution & novelty

This research work provides contributions to healthcare operations management. The contributions are through the application of the FRAM, DynaFRAM, and reinforcement learning approaches as follows:

1. Very few attempts have been made where the literature related to the FRAM is comprehensively reviewed. Therefore, there was a clear need to conduct a review article of the published studies associated with the application of FRAM to categorize its aims, domains, possible deficiencies, and other ambiguous points. The review article revealed the suitability of the FRAM in modeling complex socio-technical systems and monitoring what happens in their daily operations. The outcomes of this review could be helpful for academics, scholars, and practitioners who study, research, and work in the field of complex socio-technical systems. It also showed that the FRAM should be upgraded by exploiting supplementary methods to enhance its analytical and computational capacity to help analysts and managers in complex socio-technical systems.

2. The outcomes of the review article showed that the existing FRAM related tools were not able to monitor processes and characterize variability in neither functional outputs nor in the outcomes of the entire system. To the knowledge of the author, no attempt has so far been made to address variability-related deficiencies of the existing FRAM-related tools. This work, seemingly the first time, examines the ability of a FRAM-related tool (DynaFRAM) to visualize

daily operations of healthcare and to characterize the variability observed in the outcomes of both functions and the entire system. Another contribution of using the DynaFRAM is to characterize time-related variations during the transition process.

3. A synthesis of the FRAM related studies revealed that no studies to date have fully modelled daily operations of hospital to home transition processes. Activities related to both pre-discharge and post-discharge processes (admission to readmission) are investigated. To this end, the current study selects the FRAM to represent a functional model of the complexity of interactions among different elements/functions of the hospital-to-home transition process. This includes a comprehensive library of functions that map a hospital-to-home transition process.

4. Until the time of writing this thesis, the author has not been able to find studies that show an application of the FRAM in monitoring the functionality of the transition process and identifying the challenges of the transition process. This study employs the DynaFRAM, a dynamic version of the FRAM, to monitor frail patients' transitions to identify the potential pathways of both successful and unsuccessful transitions. It is also employed to identify challenges frail patients face during the transition process based on the performance variability observed in the outputs of functions.

5. Most of the work in hospital to home transition processes deals with using the FRAM to model the transition process and to understand variability related to its daily operations. Even though the FRAM has been used with other

quantitative approaches to quantify variability, there is no evidence of using machine learning associated techniques to assess the performance of complex operations. This study introduces an approach to couple the FRAM to reinforcement learning (RL) to explore functional environments. The approach is a novel way of employing an artificial agent who plays the role of a patient and responds to reward values assigned to functional parameters. The agent explores a functional model of the transition process generated by the FRAM to identify the functional pathways that have potential to affect the performance of the transition process. This is a basic method to provide guidance on how to provide the best care to frail patients during the transition process.

1.10. A comparison of relevant studies

As this thesis investigates the application of the FRAM to healthcare operations, a comparison of the relevant studies is of great importance. Table 1.3 shows a list of studies that have used the FRAM to address issues related to healthcare systems. The characteristics of this PhD research project are compared with other relevant studies in the healthcare sector based on data collection approaches, features, objectives, and methods to meet the objectives. It should be noted that Table 1.3 includes the data collection approaches, methods, and features used by this PhD research work to meet its objectives. It is obvious that other studies mentioned in Table 1.3 might have used other data collection approaches, methods, and features to meet their own objectives. The emphasis here is to highlight the unique characteristics of this PhD research.

Table 1.3: The characteristics of this research versus other relevant studies in the healthcare sector.

Study	Data collection approach						Method[4]			Feature			Objective			
	Observation	Interview	Focus group	Textual review	Home observations	Questionnaire	FRAM	DynaFRAM	Reinforcement learning	Frailty	Pre-discharge	Post-discharge	Comprehensive model	Patient monitoring	Challenges	Optimization
This research	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(O'Hara et al., 2020)	✓	✓	✓				✓			✓	✓	✓	✓			
(Buikstra et al., 2020)		✓	✓	✓			✓			✓	✓		✓			
(Damen et al., 2019)		✓					✓									
(Schutijser et al., 2019)	✓	✓					✓									
(Kaya et al., 2019)	✓	✓					✓									
(Rosso & Saurin, 2018)	✓	✓		✓			✓									
(McNab et al., 2018)		✓					✓									
(Raben, Viskum, et al., 2018)	✓	✓	✓	✓			✓									
(Ross et al., 2018)	✓	✓				✓	✓									
(Pickup et al., 2017)	✓	✓		✓			✓									
(Saurin & Werle, 2017)	✓	✓		✓		✓	✓									
(Clay-Williams et al., 2015)			✓				✓									
(Laugaland et al., 2014)	✓	✓					✓			✓	✓					
(Pereira, 2013)			✓				✓									

[4] DynaFRAM is not a method. It is a complementary tool for the FRAM.

1.11. Co-authorship statement

The idea behind this work was originally proposed by Prof. Brian Veitch from the Faculty of Engineering and Applied Science. Prof. Veitch was interested to see how a transition process can be mapped, a patient's transition process can be monitored, and a functional environment can be explored using an artificial agent. Applications of mapping transition processes, monitoring patients' transitions, and exploring functional environments using agents should have positive influence on healthcare professionals' perspectives in similar situations. Dr. Doug Smith from the Faculty of Engineering and Applied Science has contributed to this work by directing the author to the required areas of knowledge pertinent to systemic complexity, functional modeling, and variability visualization. He has also contributed to this work by conceptualizing and developing the DynaFRAM software. Moreover, he contributed to shaping the interview questions for gathering the data required to build the model. This work is produced after a constant and continuous feedback from Prof. Veitch and Dr. Smith on related material that the author discovered, and that the author produced in terms of modelling and testing processes and scenarios using FRAM, DynaFRAM, and reinforcement learning. The co-author Trung Tien Tran programmed the reinforcement learning part (Chapter 5).

The author was responsible for composing this thesis. He (the author) conducted the literature review, developed the functional model of the transition process, tested the model for different patient case studies, and finally investigated the role of an artificial agent to explore a functional environment based on reinforcement learning principles. The author used a set of data collected by our colleagues at the University of New Brunswick in 2019 for modelling, validating, and testing the functional model of the transition process. In this respect, the author generated new knowledge pertinent to this study. Conclusions were drawn based on which recommendations are presented.

References

Aase, K., & Waring, J. (2020). Crossing boundaries: Establishing a framework for researching quality and safety in care transitions. *Applied Ergonomics,* 89, 103228.

Aydon, L., Hauck, Y., Murdoch, J., Siu, D., & Sharp, M. (2018). Transition from hospital to home: parents' perception of their preparation and readiness for discharge with their preterm infant. *Journal of Clinical Nursing*, *27*(1–2), 269–277.

Barnhart, S. L., & Carpenter, A. (2016). Transition from hospital to home. In *Caring for the Ventilator Dependent Child* (pp. 89–119). Springer.

Bickley, S. J., & Torgler, B. (2021). A systematic approach to public health–Novel application of the human factors analysis and classification system to public health and COVID-19. *Safety science*, *140*, 105312.

Buikstra, E., Strivens, E., & Clay-Williams, R. (2020). Understanding variability in discharge planning processes for the older person. *Safety Science,* 121, 137–146.

Canadian Frailty Network (2020). Frailty matters.

Carayon, P. (2006). Human factors of complex sociotechnical systems. *Applied ergonomics*, *37*(4), 525-535.

Clay-Williams, R., Hounsgaard, J., & Hollnagel, E. (2015). Where the rubber meets the road: using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines. *Implementation Science*, 10(1), 125.

Damen, N. L., de Vos, M. S., Moesker, M. J., Braithwaite, J., van Wijngaarden, R. A. F. de L., Kaplan, J., Hamming, J. F., & Clay-Williams, R. (2019). Preoperative anticoagulation management in everyday clinical practice: an international comparative analysis of work-as-done using the functional resonance analysis method. *Journal of Patient Safety,* 17(3), 157-165.

Dhalla, I. A., O'Brien, T., Ko, F., & Laupacis, A. (2012). Toward safer transitions: how can we reduce post-discharge adverse events. *Healthcare Quarterly,* 15, 63-67.

Ebrahimi, Z., Wilhelmson, K., Eklund, K., Moore, C. D., & Jakobsson, A. (2013). Health despite frailty: exploring influences on frail older adults' experiences of health. *Geriatric Nursing,* 34(4), 289–294.

Fried, L. P., Tangen, C. M., Walston, J., Newman, A. B., Hirsch, C., Gottdiener, J., Seeman, T., Tracy, R., Kop, W. J., & Burke, G. (2001). Frailty in older adults: evidence for a phenotype. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* 56(3), M146–M157.

Heuberger, R. A. (2011). The frailty syndrome: a comprehensive review. *Journal of Nutrition in Gerontology and Geriatrics,* 30(4), 315–368.

Holden, R. J., Carayon, P., Gurses, A. P., Hoonakker, P., Hundt, A. S., Ozok, A. A., & Rivera-Rodriguez, A. J. (2013). SEIPS 2.0: a human factors framework for studying and improving the work of healthcare professionals and patients. *Ergonomics,* 56(11), 1669–1686.

Erik, H. (2017). FRAM: the functional resonance analysis method: modelling complex socio-technical systems. CRC Press.

Hollnagel, E., & Braithwaite, J. (2019). Resilient health care. CRC Press.

Isenberg, S. R., Killackey, T., Saunders, S., Scott, M., Ernecoff, N. C., Bush, S. H., ... & Mahtani, R. (2021). "Going Home [Is] Just a Feel-Good Idea With No Structure": A Qualitative Exploration of Patient and Family Caregiver Needs When Transitioning From Hospital to Home in Palliative Care. *Journal of Pain and Symptom Management,* 62(3), e9-e19.

Kaya, G. K. (2021). A system safety approach to assessing risks in the sepsis treatment process. *Applied Ergonomics*, *94*, 103408.

Kaya, G. K., Ovali, H. F., & Ozturk, F. (2019). Using the functional resonance analysis method on the drug administration process to assess performance variability. *Safety Science*, 118, 835–840.

Kianfar, S., Carayon, P., Hundt, A. S., & Hoonakker, P. (2019). Care coordination for chronically ill patients: identifying coordination activities and interdependencies. *Applied Ergonomics*, *80*, 9–16.

Kiran, T., Wells, D., Okrainec, K., Kennedy, C., Devotta, K., Mabaya, G., ... & O'Campo, P. (2020). Patient and caregiver priorities in the transition from hospital to home: results from province-wide group concept mapping. *BMJ Quality & Safety,* 29(5), 390-400.

Laugaland, K., Aase, K., & Barach, P. (2012). Interventions to improve patient safety in transitional care–a review of the evidence. *Work*, *41*(Supplement 1), 2915–2924.

Laugaland, K., Aase, K., & Waring, J. (2014). Hospital discharge of the elderly-an observational case study of functions, variability and performance-shaping factors. *BMC Health Services Research,* 14(1), 365.

Li, J., Young, R., & Williams, M. V. (2014). Optimizing transitions of care to reduce rehospitalizations. *Cleveland Clinic Journal of Medicine,* 81(5), 312-320.

McNab, D., Freestone, J., Black, C., Carson-Stevens, A., & Bowie, P. (2018). Participatory design of an improvement intervention for the primary care management of possible sepsis using the Functional Resonance Analysis Method. *BMC Medicine*, *16*(1), 174.

Nuernberger, K., Atkinson, S., & MacDonald, G. (2018). Seniors in Transition: Exploring Pathways Across the Care Continuum. *Healthcare Quarterly,* 21(1), 10-12.

O'Hara, J. K., Baxter, R., & Hardicre, N. (2020). 'Handing over to the patient': A

FRAM analysis of transitional care combining multiple stakeholder perspectives. *Applied Ergonomics,* 85, 103060.

Oeppen, J., & Vaupel, J. W. (2004). Demography. Broken limits to life expectancy. Science of human ageing. *FEBS Lett,* 571, 243–247.

Organization, W. H. (2015). World report on ageing and health. *World Health Organization*.

Patriarca, R., Di Gravio, G., Woltjer, R., Costantino, F., Praetorius, G., Ferreira, P., & Hollnagel, E. (2020). Framing the FRAM: A literature review on the functional resonance analysis method. *Safety Science*, *129*, 104827.

Pickup, L., Atkinson, S., Hollnagel, E., Bowie, P., Gray, S., Rawlinson, S., & Forrester, K. (2017). Blood sampling-Two sides to the story. *Applied Ergonomics*, *59*, 234–242.

Pereira, A. G. (2013). Introduction to the Use of FRAM on the effectiveness assessment of a radiopharmaceutical Dispatches process.

Raben, D. C., Viskum, B., Mikkelsen, K. L., Hounsgaard, J., Bogh, S. B., & Hollnagel, E. (2018). Application of a non-linear model to understand healthcare processes: using the functional resonance analysis method on a case study of the early detection of sepsis. *Reliability Engineering & System Safety*, *177*, 1–11.

Randriambelonoro, M., Perrin, C., Blocquet, A., Kozak, D., Fernandez, J. T., Marfaing, T., Bolomey, E., Benhissen, Z., Frangos, E., & Geissbuhler, A. (2020). Hospital-to-home transition for older patients: Using serious games to improve the motivation for rehabilitation–a qualitative study. *Journal of Population Ageing*, 1–19.

Rennke, S., Nguyen, O. K., Shoeb, M. H., Magan, Y., Wachter, R. M., & Ranji, S. R. (2013). Hospital-initiated transitional care interventions as a patient safety strategy: a systematic review. *Annals of Internal Medicine*, *158*(5_Part_2), 433–440.

Robinson, C. A., Bottorff, J. L., Lilly, M. B., Reid, C., Abel, S., Lo, M., & Cummings, G. G. (2012). Stakeholder perspectives on transitions of nursing home residents to hosRobinson, C. A., Bottorff, J. L., Lilly, M. B., Reid, C., Abel, S., Lo, M., & Cummings, G. G. (2012). Stakeholder perspectives on transitions of nursing home residents to hospital eme. *Journal of Aging Studies,* 26(4), 419–427.

Ross, A., Sherriff, A., Kidd, J., Gnich, W., Anderson, J., Deas, L., & Macpherson, L. (2018). A systems approach using the functional resonance analysis method to support fluoride varnish application for children attending general dental practice. *Applied Ergonomics*, *68*, 294–303.

Rosso, C. B., & Saurin, T. A. (2018). The joint use of resilience engineering and lean production for work system design: a study in healthcare. *Applied Ergonomics*, *71*, 45–56.

Salehi, V., Hanson, N., Smith, D., McCloskey, R., Jarrett, P., & Veitch, B. (2021). Modeling and analyzing hospital to home transition processes of frail older adults using the functional resonance analysis method (FRAM). *Applied Ergonomics,* 93, 103392.

Salehi, V., Veitch, B., & Smith, D. (2021). Modeling complex socio-technical systems using the FRAM: A literature review. *Human Factors and Ergonomics in Manufacturing & Service Industries,* 31(1), 118-142.

Saurin, T. A., & Werle, N. J. B. (2017). A framework for the analysis of slack in socio-technical systems. *Reliability Engineering & System Safety*, *167*, 439–451.

Schutijser, B. C. F. M., Jongerden, I. P., Klopotowska, J. E., Portegijs, S., de Bruijne, M. C., & Wagner, C. (2019). Double checking injectable medication administration: Does the protocol fit clinical practice? *Safety Science*, *118*, 853–860.

Vicente, K. J. (1999), Cognitive Work Analysis, Lawrence Erlbaum Associates, Mahwah, NJ.

Williams, S., Nolan, M., & Keady, J. (2009). Relational practice as the key to ensuring quality care for frail older people: discharge planning as a case example. *Quality* *in Ageing and Older Adults,* 10(3), 44.

Zhou, H., Roberts, P. A., & Della, P. R. (2021). Nurse-caregiver communication of hospital-to-home transition information at a tertiary pediatric hospital in Western Australia: A multi-stage qualitative descriptive study. *Journal of Pediatric Nursing,* 60, 83-91.

Chapter 2

Modelling complex socio-technical systems using the FRAM: A literature review*

Co-authorship statement. A version of this chapter has appeared as an article in the journal titled *Human Factors and Ergonomics in Manufacturing & Service Industries* published by *Wiley* publishing company. Author Vahid Salehi led the writing of this review paper including, the literature review, results, and discussion. The co-authors Prof. Brian Veitch and Dr. Doug Smith supervised this study. All authors participated in discussions that helped enhance the concepts presented in the discussion section of this paper. All authors revised, edited, and made recommendations for improvements to earlier drafts of this paper.

Abstract. This is a review paper of studies that have employed the functional resonance analysis method (FRAM). FRAM is a relatively new systemic method for modeling and analyzing complex socio-technical systems. This review aims to address the following research questions: a) Why is FRAM used? b) To what domains has FRAM been applied? c) What are the appropriate data collection approaches in practice? d) What are the deficiencies of FRAM? A review of 52 FRAM-related studies published between 2010 and 2020 revealed that FRAM-based models can be

* Salehi, V., Veitch, B., & Smith, D. (2021). Modeling complex socio-technical systems using the FRAM: A literature review. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *31*(1), 118-142. https://doi.org/10.1002/hfm.20874

used as a basis for improving safety management, accident/incident investigation, hazard identification/risk management, and complexity management in complex socio-technical systems. The outcomes also showed that healthcare was the most common domain that employed FRAM (31% of the investigated studies). The results of exploring data collection methods indicated a mixed method (interview, focus group, observation) was employed in 52% of the analyzed studies, and the accident investigation report was the most popular approach in aviation-related studies. An investigation of the deficiencies of the FRAM showed that it should be upgraded by exploiting supplementary methods to enhance its analytical and computational capacity to help risk analysts and safety managers in complex socio-technical systems.

Keywords: Complex socio-technical systems; Functional Resonance Analysis Method (FRAM); Safety management; Accident investigation; Hazard identification; Complexity management.

2.1. Introduction

2.1.1. Background

Complex socio-technical systems consist of some subsystems and sub-activities linked in known or unknown ways (Hollnagel, 2012). Examples of socio-technical systems include healthcare, aviation, manufacturing, power industry, and automotive (Soliman & Saurin, 2017). They are inherently complex, non-linear, uncertain, and dynamic (Jensen & Aven, 2018). Complex relationships between humans and their environments, including technologies and organizations, show that safety is not a linear and straightforward process in such systems (Grant et al., 2018). In the Safety-I[6] perspective, the focus is on reducing adverse outcomes, such as accidents, incidents, and near misses (Hollnagel, 2018). The core idea of the established techniques for analyzing risks and accidents in the Safety-I approach is based on event chains: unexpected outcomes and potential accidents cannot be anticipated by considering event chains or possible component failures in complex socio-technical systems (Leveson, 2011). The behavior of a complex socio-technical system does not necessarily depend on the behavior of components.

Complex socio-technical systems generally consist of elements/functions, including technologies, humans, and organizations (Hollnagel, 2012b). The tools associated with Safety-I do not consider possible connections and dependencies among the three elements to model accidents and analyze risks (Grant et al., 2018). The interactions among the elements are of great importance because they might be non-linear and dynamic (Hollnagel, 2012b; Stanton et al., 2019). The non-linear nature of the dependencies might result in intensifying undesired consequences of complex systems (Bjerga et al., 2016). Further, there is a shift from “human error” to “human performance variability” in analyzing risks and accidents in complex systems (Hollnagel, 2012b). The conventional tools do not have the capability to understand risks related to performance variability (Albery et al., 2016). Thus, there is a clear need to shift from conventional approaches to systemic methods to address safety and risk-related issues in complex socio-technical systems (Costantino et al., 2018).

[6] Safety-I: safety is defined as a state where as few things as possible go wrong because of identifiable failures/malfunctions related to specific components, such as technology, the human workers, procedures, and the organizations in which they are embedded. The aim is to identify the causes of adverse outcomes (Hollnagel, 2018).

2.1.2. Functional resonance analysis method (FRAM)

Safety-II[7] perspective is associated with the capability of systems to succeed under varying situations. From this perspective, performance adjustments/adaptations are required to respond to varying situations (Hollnagel, 2018). The functional resonance analysis method (FRAM), a Safety-II approach, is a function-based systemic approach for investigating safety-related problems and challenges in complex socio-technical systems (Hollnagel, 2012b). It has become popular over the last decade as a new method to help safety and risk management. Unlike the majority of the conventional risk assessment approaches that concentrate on the root causes of failures, the focus of FRAM is on understanding how functions/activities can be coupled and how the amalgamations of the variability of everyday operations/activities might result in undesired and unexpected results (Hulme et al., 2019; Ten & Hassim, 2019).

From a systemic/FRAM perspective, unacceptable outcomes like accidents are seen as emergent and typically are not simply attributable to only human failures or broken components. That is, the relationships among components, inputs and outputs, as well as causes and effects, lead to emerging desired/expected and undesired/unexpected consequences (Hollnagel, 2012b). Thus, FRAM investigates the dynamics of the complex socio-technical systems instead of computing the probability of failures (Ross et al., 2018). The dynamic nature of complex socio-technical systems, along with singular variability of functions, might lead to undesired outcomes (Hollnagel,

[7] Safety-II: safety is defined as a state where as many things as possible go right. It is related to the ability of systems to succeed under varying conditions. The aim is to respond to varying conditions based on adaptations provided by everyday performance variability (Hollnagel, 2018).

2012b). As such undesired/unexpected outcomes are prone to accidents, complex socio-technical systems aim to deal adequately with them (Bjerga et al., 2016). Therefore, monitoring and controlling variability is of considerable importance for avoiding accidents.

FRAM describes how complex socio-technical systems function (Bjørnsen et al., 2020). It emphasizes functional aspects, dynamic interactions, and performance variability, rather than physical aspects (Sujan et al., 2018). Performance variability refers to the point that the performance of the same task or activity will vary over time as the conditions of systems for performance are not constant over time (Hollnagel, 2012b). An example could be different sales figures for similar retail stores in similar neighborhoods, or different efficiency rates for similar nurses at similar hospitals during a year. To realize the behaviors of functions and their outputs, FRAM focuses on four underlying principles that are explained as follows (Hollnagel, 2012b):

a) The equivalence of successes and failures

The first principle emphasizes that what goes right and what goes wrong occur in a similar way. Indeed, it assumes acceptable and unacceptable outcomes are associated with the capabilities of individuals, groups, and organizations to adjust to new changes and to adapt themselves to expected and unexpected occurrences (Hollnagel, 2012b).

b) Approximate adjustment

In order to go right, work should be continuously adjusted to existing work conditions, such as resources, information, time, requirements, tools, and interruptions. The adjustments will be approximate instead of precise because resources, including material, time, and information, are always finite and underspecified (Hollnagel, 2012b).

c) Emergent outcomes

According to the third principle, acceptable as well as unacceptable results can emerge from variability related to everyday adjustments, instead of resulting from cause-effect relationships pertaining to the failure of particular components (Hollnagel, 2012b).

d) Functional resonance

The variability of a singular task/function is not generally large enough to be the root cause of a system failure. The fourth concept refers to the fact that the weak variability of a number of tasks/functions interrelating with each other might intensify each other and lead to amplifying the variability of the entire system (Hollnagel, 2012b).

2.1.3. How to implement FRAM in practice

The four main steps of using FRAM to model and analyze complex socio-technical systems are as follows (Hollnagel, 2012):

1) Identifying and describing necessary system tasks/activities/functions;
2) Characterizing the variability of each identified task/activity/function;
3) Looking for functional resonance (aggregation of variability); and
4) Identifying solutions for keeping work operations in acceptable conditions.

The first step of FRAM involves identifying and describing the essential functions of a system, including technological, human, and organizational activities of everyday work (Schutijser et al., 2019). Functions are explained based on the six following aspects (Hollnagel, 2012b):

- Input: what (material, energy, or information) starts a function/task;
- Output: the result of what a function/task produces;
- Precondition: what should be verified before carrying out a function/task;
- Resource: what (matter, energy, information, competence, software, tools, manpower) is required or consumed by a function to produce the Output;
- Control: what (guidelines, plans, procedures) regulates a function for producing the Output;
- Time: it can influence how a function/task is performed. It can be a limitation or a resource.

In FRAM literature, there are two types of function: background and foreground. Background functions have only Input(s) or an Output(s) and can be assumed to be constant when the system is analyzed. On the other hand, foreground functions have at least two active aspects (Hollnagel, 2012b).

The second step includes characterizing the potential and actual (observed) variability associated with functions specified in the first step (Hollnagel, 2012b). Technological, human, and organizational functions account for three major sources of the variability in complex systems (W. Li et al., 2019). It is essential to describe the variability once its possible sources are identified. The simple approach to describe the variability of the Output of a function is in terms of time and precision. Variability encompasses three major types: internal (endogenous), external (exogenous), and upstream-downstream couplings (Hollnagel, 2012b). Buikstra et al. (2020), for instance, characterized the variability observed in the output of the function <to organize the day of discharge> in the process of discharge planning for patients. The variability was observed in discharge communication, staff availability, support service provision, and estimated discharge date. To gain more information about variability and its types, see Hollnagel (2012b).

The third step encompasses functional resonance or aggregate variability. It is performed based on the couplings or dependencies among functions and their potential/actual variability. Couplings mean that the Output of a function can be linked to different aspects of other functions. This step shows how the variability of a function might influence other functions, and how the variability of two or more functions can intensify each other so that the situation becomes unstable and leads to unexpected outcomes (Alvarenga et al., 2014).

The fourth step of FRAM includes some recommendations to identify solutions for retaining work operations in normal conditions (Hollnagel, 2012b). This step aims at identifying safety barriers to limit the aggregation of the variability (Alvarenga et al., 2014).

Figure 2.1 shows an example of a simple FRAM model. It must be mentioned that it is not a real-world model. It is presented to help understand the concepts mentioned in FRAM literature. According to the figure, there are eight functions in the model, and each function has six aspects. Moreover, there is a coupling or dependency between Functions A and D, but there is no coupling between Functions A and B. Function A is an example of a background function, and Function D is an example of a foreground function. FRAM Model Visualiser (FMV) software introduced by Hill and Hollnagel (2016) is a tool that can be used to map and model complex socio-technical systems to monitor variability in the systems.

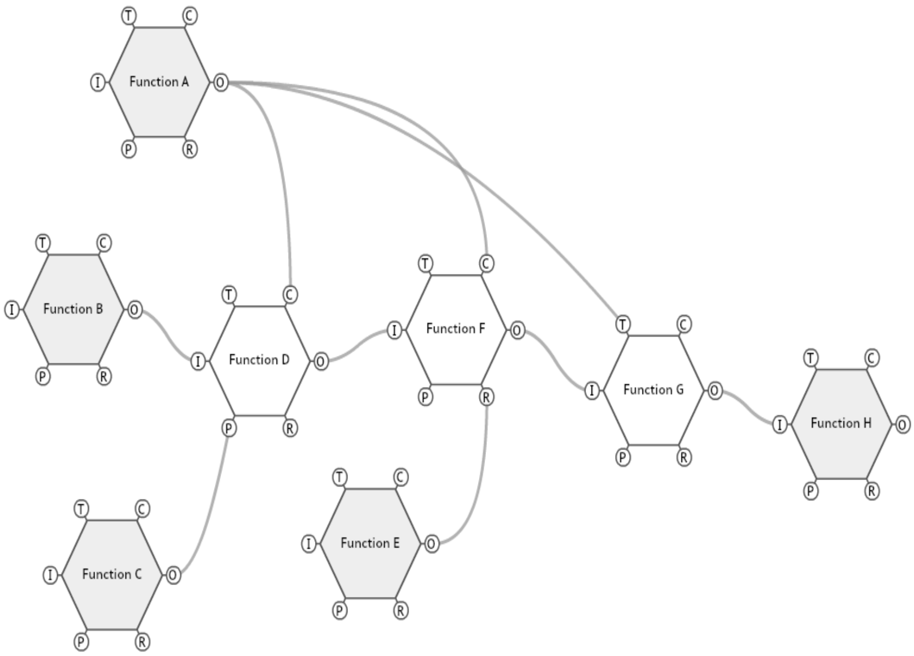

Figure 2.1: An example of a simple FRAM model. The hexagons represent functions including six aspects (input (I), output (O), precondition (P), resource (R), time (T), and control (C)). Background and foreground functions have been shown in gray and white colors, respectively. The figure also contains the couplings between the functions.

2.1.4. The research questions and aims

Subsections 2.1.2 and 2.1.3 explained what FRAM is and how it can be applied in practice. A considerable number of studies have employed FRAM in different domains for different purposes. Therefore, there is a clear need to conduct a review paper of the published studies associated with the application of FRAM in order to categorize its aims, domains, possible deficiencies, and other ambiguous points. Such a review reveals the capability of FRAM in modeling complex socio-technical systems and monitoring what happens in their operations. This review paper aims at reporting, explaining, and analyzing the studies that have applied FRAM to map, model, or understand the complexities of socio-technical systems. The outcomes of this review could be helpful for academics, scholars, and practitioners who study, research, and work in the field of complex socio-technical systems. They could enhance their knowledge about the developments and practical applications of FRAM.

In order to enhance the quality of a review paper, clear questions and aims are required (Bergström et al., 2015). All the studies chosen for this review were methodically analyzed in terms of the following questions:

a) Why is FRAM used?

b) To what domains has FRAM been applied?

c) What are the appropriate data collection approaches in practice?

d) What are the deficiencies of FRAM?

2.2. Method

In this study, an explicit research method was used. That is, the sources/databases and the search strategy are clear. The criteria for choosing and analyzing the studies are described in detail. The concentration of this literature review is on FRAM as a method to realize, map, and analyze complex socio-technical systems. The schematic structure of article selection for this study is shown Figure 2.2.

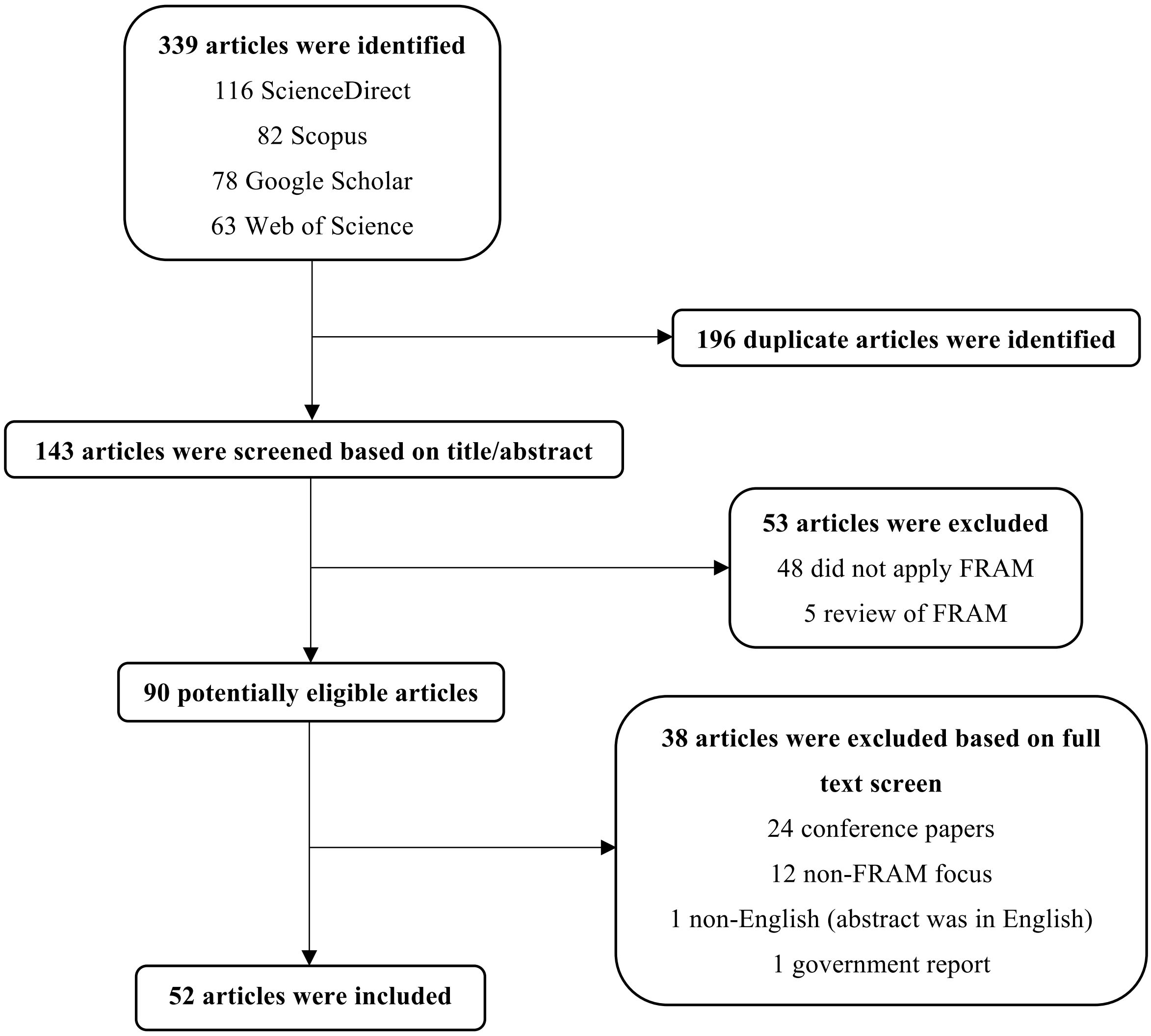

Figure 2.2: A schematic structure for article selection in the current review paper.

2.2.1. Electronic search

Four databases were searched: ScienceDirect, Scopus, Web of Science, and Google Scholar. The initial electronic search included the dates between 01 January 2010 and 31 March 2020. The search was purposefully restricted to "functional resonance analysis method" and "FRAM". All sorts of studies were considered in the initial electronic search, including research articles, review articles, conference papers, book chapters, books, and technical/official reports.

2.2.2. Eligibility criteria

The studies were chosen for review based on the following criteria:

i. Studies included an application of FRAM in complex socio-technical systems.

ii. Sources were original peer reviewed journal articles published in English.

The following exclusion criteria were considered:

i. Books, book chapters, review papers, conference papers, and reports.

ii. Sources published in a language other than English.

2.2.3. Data extraction, organization, and interpretation

The study information extracted includes the following categories: (i) study/year; (ii) study/publication title; (iii) domain type; (iv) data collection approach; (v) method(s); (vi) function type; (vii) variability; and (viii) objective(s)/outcomes. The extracted data and information were synthesized so that the research questions of the current review could be addressed. The information and data are summarized qualitatively and quantitatively in tables and figures in the Results section. They will be described and interpreted in detail for responding to the research questions.

2.3. Results

2.3.1. The results of the electronic search and full text selection

The results of the search were 339 studies, containing 116, 82, 78, and 63 for ScienceDirect, Scopus, Google Scholar, and Web of Science, respectively. After removing duplicate studies, 143 studies were identified (Figure 2.2). Figure 2.3 indicates the number of studies published per year between January 1, 2010 and March 31, 2020. According to the figure, the number of studies about FRAM has gradually increased from 2010 to 2020. The results of the initial search indicate that FRAM is becoming more popular.

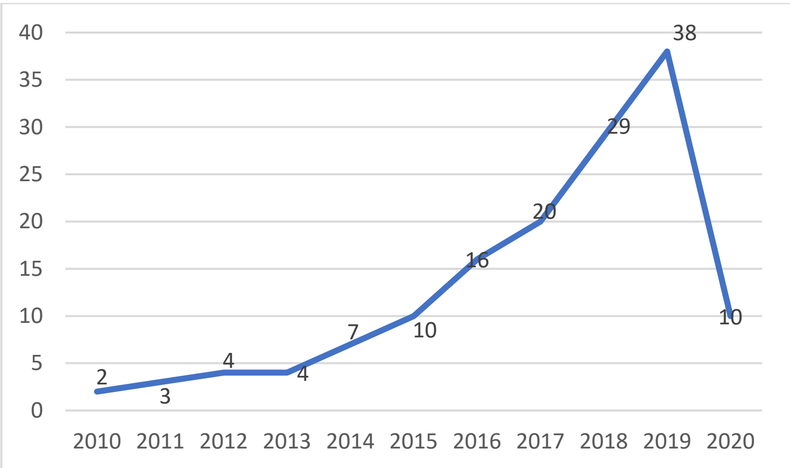

Figure 2.3: The number of studies, including research and review articles, books, conference papers, and reports published from 2010 to 2020 (March).

After examining titles and abstracts, 53 articles were excluded. The decision for excluding these 53 articles was based on: (i) method eligibility that showed 48 articles did not use FRAM; and (ii) five articles included reviews of FRAM literature. Then, 90 potentially eligible articles remained. Screening the full texts of the 90 articles led to the exclusion of a further 38 articles (24 conference papers, 12 non-FRAM focus, one non-English article, and one report). As shown in Figure 2.2, a total of 52 FRAM studies were included for full text review.

The 52 selected articles were categorized based on publication title. The results showed that "Reliability Engineering and Systems Safety" and "Safety Science" accounted for 21% (n=11) and 15% (n=8) of the analyzed studies, respectively. Additionally, "Cognition, Technology & Work" with 12% (n=6), "Applied Ergonomics" with 10% (n=5), and "Journal of Loss Prevention in the Process Industries" with 8% (n=4) were also venues in which FRAM publications appeared in some numbers.

The information extracted from the 52 reviewed articles is a basis for responding to the research questions of this study. The following subsections concentrate on how to combine and formulate the information of the reviewed articles in order to discover appropriate responses to the research questions.

2.3.2. Why is FRAM used?

The first finding of this study is related to the key role of FRAM in complex socio-technical systems. The 52 studies were categorized in terms of their objectives (Table

2.1). The four following subsections are presented to reply to the first research question of this review: why is FRAM used?

Table 2.1: Categorizing the analyzed studies in terms of objective/aim*.

Safety management	Accident/incident investigation	Hazard identification/risk management	Complexity management
Buikstra et al. (2020)	Lee et al. (2019)	Yu et al. (2020)	Ferreira & Cañas (2019)
O'Hara et al. (2020)	Gao et al. (2019)	Li et al. (2019)	França et al. (2019)
Smith et al. (2020)	Huang et al. (2019)	Jensen & Aven (2017)	Adriaensen et al. (2019)
Damen et al. (2019)	Bridges et al. (2018)	Anvarifar et al. (2017)	McNab et al. (2018)
Schutijser et al. (2019)	Lee & Chung (2018)	Saurin & Werle (2017)	de Vries (2017)
Gao et al. (2019)	Smith et al. (2018)	Zheng et al. (2016)	Furniss et al. (2016)
Patriarca et al. (2018)	Yang et al. (2017)	Tian et al. (2016)	Toroody et al. (2016)
Bridges et al. (2018)	Studic et al. (2017)	Fukuda et al. (2016)	De Carvalho (2011)
Ross et al. (2018)	Patriarca, Bergström, et al. (2017)	Duan et al. (2015)	Belmonte et al. (2011)
Wachs et al. (2018)	Patriarca, Di Gravio, & Costantino (2017)	Rosa et al. (2015)	Herrera & Woltjer (2010)
Patriarca, Di Gravio, Costantino, et al. (2017)	Hirose et al. (2016)		
Patriarca & Bergström (2017)	Toroody et al. (2016)		
Pickup et al. (2017)			
Aguilera et al. (2016)			
Laugaland et al. (2014)			

* It must be mentioned that seven of the 52 analyzed studies applied FRAM for other objectives. System design: Rosso & Saurin (2018); Wachs & Saurin (2018); Elements/factors identification: Raben, Bogh, et al. (2018), Raben, Viskum, et al. (2018), Praetorius et al. (2015); Reconciling differences between work-as-imagined and work-as-done: Clay-Williams et al. (2015); operation analysis: Smith et al. (2017).

2.3.2.1. Safety management

The results presented in Table 2.1 confirmed that 29% (15 out of 52) of the studies investigated safety management related problems in complex socio-technical systems. Seven studies concentrated on patients' safety and health, or other issues associated with the healthcare sector, and eight studies employed FRAM for managing safety in other sectors. Buikstra et al. (2020), Laugaland et al. (2014), and O'Hara et al. (2020) conducted FRAM-related studies to improve safety and health of frail older people in transition processes from hospital to home. Raben, Bogh, et al. (2018) and Raben, Viskum, et al. (2018) employed FRAM to identify contributing factors affecting healthcare safety systems. Pickup et al. (2017) indicated that FRAM is able to identify the reasons for variability and to highlight the restrictions in understanding factors affecting performance in healthcare systems. The ability of FRAM to recognize important functions that contribute to patient safety improvement was confirmed by Damen et al. (2019). Other studies showed safety management can be improved by integrating FRAM and resilience concepts (Aguilera et al., 2016; Smith et al., 2020). In total, the results of the 15 investigated studies confirmed that FRAM can play a constructive role in improving the safety management of complex socio-technical systems.

2.3.2.2. Accident/incident investigation

According to Table 2.1, the purpose of 23% (12 out of 52) of the analyzed studies was accident or incident investigation. This percentage of application shows the importance of FRAM in addressing issues associated with accidents or incidents in complex socio-technical systems. The results of some studies that employed FRAM for accident/incident investigation are described here. Tian et al. (2016) explicitly highlighted the role of FRAM in identifying and explaining factors that affect accidents in a transportation system. The results of the FRAM model provided more details to investigate about the causes of the accidents. As Table 2.1 shows, a few of the studies had dual aims. Gao et al. (2019), as an example, investigated safety regulations intended to prevent accidents. The study employed FRAM to categorize safety regulatory functions and to suggest some safety restrictions to limit the consequences of major accidents. In the study, the sources of variability were explored in terms of technical, human, and organizational aspects of the given system. Moreover, the variations related to each regulatory function were identified. Huang et al. (2019), Lee et al. (2019), and Lee & Chung (2018) highlighted the use of FRAM to facilitate the accident investigation process. Huang et al. (2019) investigated an accident report for analyzing what happened in a railway-related accident using FRAM. The functions that contributed to the accident were identified, and relevant barriers were added to the functions to prevent similar accidents.

2.3.2.3. Hazard identification and risk management

Identifying latent hazards can help analysts to manage risks in complex socio-technical systems (Fukuda et al., 2016). 19% (10 out of 52) of the investigated studies concentrated on identifying hazards to facilitate the process of risk management (Table 2.1). FRAM has been used to proactively discover the potential hazards in complex socio-technical systems (Duan et al., 2015; Zheng et al., 2016). Yu et al. (2020) employed FRAM to comprehend the emergent consequences of function interactions that can lead to hazards in a complex process industry system. The capability of FRAM was examined by Li et al. (2019) as a foundation to develop a risk assessment framework for operational processes. Jensen & Aven (2017) introduced an integrated approach including FRAM for identifying hazards and threats in complex operations. Anvarifar et al. (2017) identified threats and opportunities in designing flood defense using FRAM. They analyzed internal and external variations/changes to find ways to improve the risk management of the investigated system. Finally, Rosa et al. (2015) applied FRAM to construction-related operations to understand how the system functions and to identify potential hazards for assessing risk through recognizing performance variability.

2.3.2.4. Complexity management

The results presented in Table 2.1 show that 19% (10 out of 52) of the reviewed studies employed FRAM to investigate complexity in socio-technical systems. It is noteworthy that some of the 10 FRAM-based studies investigated other purposes in addition to complexity. In this study, the complexity of socio-technical systems is investigated through decomposition and coupling. Decomposition means the systems are decomposed in the functions they perform, not in their structure (Dekker et al., 2011). Coupling refers to interdependencies or relationships between functions (Grant et al., 2018).

The functions identified in the analyzed studies are summarized in Table 2.2 and shown in a Venn diagram in Figure 2.4. According to the results presented in Figure 2.4 and Table 2.2, in most of the analyzed studies, technological, human, and organizational functions were considered and investigated to show the complexity of the investigated systems. 96% (50 out of 52) of the analyzed studies considered human functions, and 85% (44 out of 52) of the studies investigated organizational functions. Meanwhile, technological functions were investigated in 65% (34 out of 52) of those studies. In a few cases, other functions were investigated, such as environmental functions (Bridges et al., 2018; França et al., 2019; Jensen & Aven, 2017; Patriarca, Bergström, et al., 2017). The Venn diagram in Figure 2.4 shows the combinations of functions that were investigated in the analyzed studies. According to the diagram, approximately 56% (29 out of 52) of the studies considered all three functions: technological, human, and organizational. 44 of the 52 studies considered both human and organizational functions, 33 investigated human and technological functions, and 29 explored technological and organizational functions.

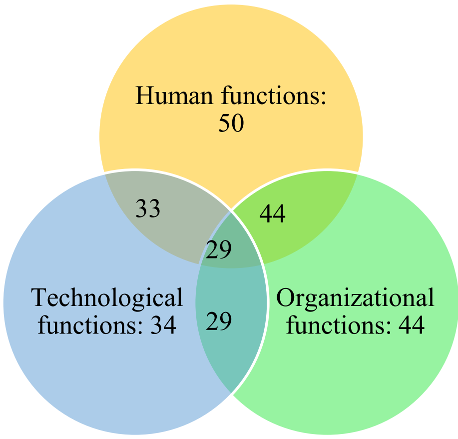

Figure 2.4: Venn diagram indicating the number of studies that explored each category of functions.

Another application of FRAM is to explore the dynamics of interactions and couplings between functions to help cope with complexity in socio-technical systems (Righi & Saurin, 2015). The results provided in Table 2.2 indicate that the couplings between the functions were investigated in a number of the analyzed studies (França et al., 2019; Jensen & Aven, 2017; Patriarca & Bergström, 2017; Ragosta et al., 2015). Franca et al. (2019) identified the relationships among different elements/functions in the system, such as machines/technology, human/workers, organization/subsystems, and environment. Jensen and Aven (2017) recognized dependencies between functions/elements to show the complexity of the system. Patriarca & Bergström (2017) explored for couplings and dependencies between the functions to improve insights about the complex processes of maritime operations.

Table 2.2: The information associated with the types of functions and variability.

Study	Function			Variability	Study	Function			Variability
	Technological	Human	Organizational			Technological	Human	Organizational	
Buikstra et al. (2020)	×	✓	✓	✓	Yang et al. (2017)	✓	✓	✓	✓
Smith et al. (2020)	×	×	×	✓	Patriarca & Bergström (2017)	✓	✓	✓	✓
Yu et al. (2020)	✓	✓	×	×	Pickup et al. (2017)	×	✓	✓	✓
O'Hara et al. (2020)	×	✓	✓	✓	Jensen & Aven (2017)	✓	✓	✓	✓
Lee et al. (2019)	×	✓	×	✓	Anvarifar et al. (2017)	×	✓	✓	✓
Ferreira & Cañas (2019)	✓	✓	✓	✓	Studic et al. (2017)	✓	✓	✓	✓
França et al. (2019)	✓	✓	✓	✓	Patriarca, Bergström, et al. (2017)	✓	✓	✓	✓
Gao et al. (2019)	✓	✓	✓	✓	Patriarca, Di Gravio, & Costantino (2017)	✓	✓	✓	✓
Damen et al. (2019)	×	✓	✓	✓	de Vries (2017)	✓	✓	✓	✓
Schutijser et al. (2019)	✓	✓	✓	✓	Saurin & Werle (2017)	✓	✓	✓	✓
Adriaensen et al. (2019)	✓	✓	✓	✓	Smith et al. (2017)	✓	✓	✓	×
Huang et al. (2019)	×	✓	✓	✓	Furniss et al. (2016)	✓	✓	✓	✓
Kaya et al. (2019)	✓	✓	✓	✓	Hirose et al. (2016)	✓	✓	✓	✓
Li et al. (2019)	×	✓	✓	✓	Zheng et al. (2016)	✓	✓	✓	✓

Patriarca et al. (2018)	✓	✓	✓	✓	Aguilera et al. (2016)	✓	✓	✓	✓
Rosso & Saurin (2018)	✓	✓	✓	✓	Tian et al. (2016)	✓	✓	✓	✓
Wachs & Saurin (2018)	×	✓	✓	✓	Toroody et al. (2016)	×	✓	✓	✓
McNab et al. (2018)	✓	✓	✓	✓	Fukuda et al. (2016)	×	✓	×	✓
Raben, Bogh, et al. (2018)	×	✓	✓	✓	Duan et al. (2015)	×	✓	✓	✓
Bridges et al. (2018)	✓	✓	×	✓	Praetorius et al. (2015)	×	✓	✓	✓
Raben, Viskum, et al. (2018)	✓	✓	×	✓	Rosa et al. (2015)	✓	×	×	✓
Ross et al. (2018)	×	✓	✓	✓	Clay-Williams et al. (2015)	×	✓	✓	✓
Lee & Chung (2018)	×	✓	✓	✓	Laugaland et al. (2014)	×	✓	✓	✓
Smith et al. (2018)	✓	✓	✓	✓	De Carvalho (2011)	✓	✓	✓	✓
Wachs et al. (2018)	✓	✓	✓	✓	Belmonte et al. (2011)	✓	✓	✓	✓
Patriarca, Di Gravio, Costantino, et al. (2017)	✓	✓	✓	✓	Herrera & Woltjer (2010)	✓	✓	✓	✓

2.3.2.5. Other objectives

A few studies applied FRAM for other objectives, although the number of the studies is limited. As illustrated in Table 2.1, FRAM has been applied for identifying factors that influence system performance (Praetorius et al., 2015; Raben, Bogh, et al., 2018; Raben, Viskum, et al., 2018). Another objective that was followed by using FRAM is to investigate system design (Rosso & Saurin, 2018; Wachs & Saurin, 2018). Finally, FRAM was employed to reconcile differences between work-as-imagined and work-as-done (Clay-Williams et al., 2015) and to analyze industrial operations (Smith et al., 2017).

2.3.3. To what domains has FRAM been applied?

FRAM has been employed successfully for different purposes in 12 different domains. The following domains and relevant examples were extracted from Table 2.3. The table indicates the domains and contexts where the 52 selected studies used FRAM. According to the table, four domains accounted for 73% of the analyzed studies: healthcare (31%, 16 out of 52), aviation (17%, 9 out of 52), maritime (17%, 9 out of 52), and railway (8%, 4 out of 52). Other domains, such as the environment (6%), process industries (6%), industrial processes (2%), and power industry (2%) constituted 27% (Table 2.3).

Healthcare was the domain to which FRAM has been most applied. The advantages of using FRAM have been highlighted in the healthcare sector by several studies. It has been employed to analyze the discharge process of frail patients in the healthcare sector (Buikstra et al., 2020; Laugaland et al., 2014; O'Hara et al., 2020). The functions involved in the process were identified, the sources of variability were investigated, and performance shaping factors were specified. FRAM was also used to investigate differences between work-as-done and work-as-imagined (Damen et al., 2019; W. Li et al., 2019; Schutijser et al., 2019). It is also able to support investigations for improving clinical procedures and processes (McNab et al., 2018; Roland, 2018; A. Ross et al., 2018).

Aviation and maritime were the next most popular domains with the same percentage of application (17%). De Carvalho (2011) applied FRAM to study a mid-air collision in order to identify the key resilience features of an Air Traffic Management system. FRAM provides adequate support for analyzing events in aviation operations, as highlighted by Adriaensen et al. (2019), Yang et al. (2017), and Hirose et al. (2016). The potential of FRAM to identify fundamental mechanisms for system performance has led to increasing its application in the operations of the maritime domain (de Vries, 2017; Lee et al., 2019; Smith et al., 2018a).

Railway was another domain to which FRAM has been applied. FRAM was successfully applied to the railway domain to identify functions that contributed to accidents (Huang et al., 2019) and to integrate human factors and technology change for managing rail traffic (Belmonte et al., 2011). Minor domains of application and the relevant examples are as follows: environment (Anvarifar et al., 2017), process industries (Smith et al., 2017), industrial operations (Gattola et al., 2018; Jensen & Aven, 2017), power industry (Wachs et al., 2018), construction (Rosa et al., 2015), manufacturing industry (Zheng et al., 2016), government (Gao et al., 2019), and human factors projects (Furniss et al., 2016).

Table 2.3: The results of the domains explored in the current review.

Study	Domain	Study	Domain
Buikstra et al. (2020)	Healthcare	França et al. (2019)	Maritime
O'Hara et al. (2020)	Healthcare	Lee & Chung (2018)	Maritime
Damen et al. (2019)	Healthcare	Smith et al. (2018)	Maritime
Schutijser et al. (2019)	Healthcare	Patriarca & Bergström (2017)	Maritime
Kaya et al. (2019)	Healthcare	de Vries (2017)	Maritime
Patriarca et al. (2018)	Healthcare	Tian et al. (2016)	Maritime
Rosso & Saurin (2018)	Healthcare	Toroody et al. (2016)	Maritime
Wachs & Saurin (2018)	Healthcare	Praetorius et al. (2015)	Maritime
McNab et al. (2018)	Healthcare	Huang et al. (2019)	Railway
Raben, Bogh, et al. (2018)	Healthcare	Patriarca, Bergström, et al. (2017)	Railway
Raben, Viskum, et al. (2018)	Healthcare	Fukuda et al. (2016)	Railway
Ross et al. (2018)	Healthcare	Belmonte et al. (2011)	Railway
Pickup et al. (2017)	Healthcare	Bridges et al. (2018)	The Environment

Saurin & Werle (2017)	Healthcare	Patriarca, Di Gravio, Costantino, et al. (2017)	The environment
Clay-Williams et al. (2015)	Healthcare	Anvarifar et al. (2017)	The environment
Laugaland et al. (2014)	Healthcare	Yu et al. (2020)	Process industries
Ferreira & Cañas (2019)	Aviation	Smith et al. (2017)	Process industries
Adriaensen et al. (2019)	Aviation	Aguilera et al. (2016)	Process industries
Yang et al. (2017)	Aviation	Smith et al. (2020)	Industrial operations
Studic et al. (2017)	Aviation	Jensen & Aven (2017)	Industrial operations
Patriarca, Di Gravio, & Costantino (2017)	Aviation	Li et al. (2019)	Industrial processes
Hirose et al. (2016)	Aviation	Gao et al. (2019)	Government
Duan et al. (2015)	Aviation	Wachs et al. (2018)	Power industry
De Carvalho (2011)	Aviation	Furniss et al. (2016)	Human factors projects
Herrera & Woltjer (2010)	Aviation	Zheng et al. (2016)	Manufacturing industry
Lee et al. (2019)	Maritime	Rosa et al. (2015)	Construction

2.3.4. What are the appropriate data collection approaches in practice?

Table 2.4 shows that a wide spectrum of data collection approaches has been used to model complex socio-technical systems by FRAM. The approaches include observation, accident investigation report, document study, interview, workshop/meeting, focus group, discussion and consultation.

The results of the analyzed studies highlighted that interviews, focus groups, observations, document analyses, and accident/incident investigation reports have been used to develop FRAM models. As shown in Table 2.4, the data required for modeling the given system came from interviews in 58% of the investigated studies

(30 out of 52). According to the table, semi-structured interviews (Damen et al., 2019; McNab et al., 2018; Schutijser et al., 2019) and structured interviews (Arie Adriaensen et al., 2019; Rosso & Saurin, 2018) were the two main types of interview used to develop FRAM models. Table 2.4 revealed that 39% (20 out of 52) of the analyzed studies employed observation as a data collection approach for developing FRAM models. Direct observation (Raben, Bogh, et al., 2018; Raben, Viskum, et al., 2018), participant and non-participant observation (Wachs & Saurin, 2018), and on-board[8] observation (França et al., 2019) were the major types of observation in the studies analyzed. Accident investigation report and document analysis were other main sources of gathering data. 29% (15 out of 52) of the investigated studies employed this approach to provide the data required for modeling by FRAM (Table 2.4). It is noteworthy that accident/incident investigation report was the most popular approach in aviation-related studies as it was employed by 70% (7 out of 10) of the investigated studies in the aviation domain (Tables 2.3 and 2.4).

The results of the analyzed studies indicated that there are approaches for validating FRAM models (Buikstra et al., 2020; Kaya et al., 2019; O'Hara et al., 2020). Workshop, meeting, group discussion, and interview with expert were used by 11.5% (6 out of 52) of the analyzed studies to validate constructed FRAM models. Conducting interviews with experts to validate the outcomes of developed FRAM models was highlighted by Kaya et al. (2019) and Bridges et al. (2018). Workshop is another appropriate approach for validating the reliability of developed FRAM models (Ross et al., 2018).

[8] On-board observation is done on a ship, aircraft, or other vehicles.

In total, a mixed method (a combination of various approaches) was used in a considerable number of the analyzed studies for developing and validating FRAM models. The results presented in Table 2.4 indicated that 52% (27 out of 52) of the studies used a mixed method. Buikstra et al. (2020), as an example, used a mixed method, including semi-structured interview, document review, and focus group to develop and validate the FRAM model. The mixed method was the most popular method in healthcare-related studies (Buikstra et al., 2020; Kaya et al., 2019; Laugaland et al., 2014; O'Hara et al., 2020). As shown in Tables 2.3 and 2.4, approximately 81% (13 out of 16) of the healthcare-related studies applied a mixed method for FRAM model development and validation.

Table 2.4: The data collection approaches of the analyzed studies.

Study	Data collection approach													
	Semi-structured interview	Structured interview	Direct observation	Participant and non-participant observation	on-board observation	Accident/incident investigation report	document analysis	Focus group	Workshop	meeting	Group/expert discussion	Simulation	Example	Questionnaire
Buikstra et al. (2020)	✓						✓	✓						
Smith et al. (2020)													✓	
Yu et al. (2020)												✓		
O'Hara et al. (2020)	✓		✓					✓						
Lee et al. (2019)						✓								
Ferreira & Cañas (2019)												✓		
França et al. (2019)		✓			✓									
Gao et al. (2019)		✓				✓	✓				✓			
Damen et al. (2019)	✓													
Schutijser et al. (2019)	✓		✓											
Adriaensen et al. (2019)		✓												
Huang et al. (2019)						✓								
Kaya et al. (2019)		✓	✓						✓					

Li et al. (2019)			✓											
Patriarca et al. (2018)		✓	✓				✓	✓						
Rosso & Saurin (2018)		✓	✓					✓						
Wachs & Saurin (2018)		✓		✓			✓							
McNab et al. (2018)	✓													
Raben, Bogh, et al. (2018)		✓	✓				✓	✓						
Bridges et al. (2018)						✓					✓			
Raben, Viskum, et al. (2018)		✓	✓				✓	✓						
Ross et al. (2018)		✓	✓						✓					
Lee & Chung (2018)						✓								
Smith et al. (2018)		✓				✓								
Wachs et al. (2018)												✓		
Patriarca, Di Gravio, Costantino, et al. (2017)	✓						✓							
Yang et al. (2017)						✓								
Patriarca & Bergström (2017)	✓						✓							
Pickup et al. (2017)	✓		✓											
Jensen & Aven (2017)			✓											
Anvarifar et al. (2017)	✓													
Studic et al. (2017)	✓		✓			✓	✓				✓			
Patriarca, Bergström, et al. (2017)						✓								

Patriarca, Di Gravio, & Costantino (2017)						✓								
de Vries (2017)	✓		✓					✓						
Saurin & Werle (2017)	✓		✓				✓							✓
Smith et al. (2017)													✓	
Furniss et al. (2016)	✓													
Hirose et al. (2016)						✓								
Zheng et al. (2016)	✓		✓				✓							
Aguilera et al. (2016)	✓		✓					✓						
Tian et al. (2016)						✓								
Toroody et al. (2016)						✓					✓			
Fukuda et al. (2016)						✓								
Duan et al. (2015)						✓								
Praetorius et al. (2015)	✓		✓					✓						
Rosa et al. (2015)											✓			✓
Clay-Williams et al. (2015)	✓									✓				
Laugaland et al. (2014)			✓								✓			
De Carvalho (2011)		✓					✓							
Belmonte et al. (2011)												✓		
Herrera & Woltjer (2010)	✓													

2.3.5. What are the deficiencies of FRAM?

Another aim of the current review is to categorize the deficiencies and weaknesses of FRAM based on the reviewed articles provided in Table 2.5. The (supplementary) methods used in the analyzed studies are summarized and shown in Table 2.5. The table shows 62% (32 out of 52) of the analyzed studies employed other approaches in addition to FRAM to achieve their goals. FRAM is a young approach and requires developments to address the issues of complex socio-technical systems. Although FRAM is useful to visualize and understand how a system functions, it suffers from the lack of quantifying the probabilities of successes and failures (Jensen & Aven, 2018). A number of the analyzed studies emphasized the lack of quantification (Belmonte et al., 2011) and highlighted that there is a clear need to identify and quantify normal and abnormal variability (Anvarifar et al., 2017; Patriarca, Di Gravio, & Costantino, 2017; Patriarca et al., 2018; Praetorius et al., 2017). Another challenge in front of FRAM is the lack of a structured method for determining recommendations and specifying safety barriers. The outcomes of some studies confirmed that it is difficult to employ FRAM to propose safety constraints in practice (Herrera & Woltjer, 2010; Praetorius et al., 2017).

The results of the analysis also indicated that the process of modeling by FRAM for helping risk assessment is time consuming, needs many resources, and hence is expensive. Three studies showed that an experienced team of experts is required to analyze and model the system (Accou & Reniers, 2019; Jensen & Aven, 2018; Pereira, 2013). In fact, the quality of the output in FRAM directly depends on the team of experts and the information they provide as input for functions. Another issue is that there is no standard for determining how much information should be included in the process of the analysis, as highlighted by Anvarifar et al. (2017), Li et al. (2019), and Patriarca, Bergström et al. (2017). Four studies conducted by Yang et al. (2017), Duan et al. (2015), Tian et al. (2016), and Zheng et al. (2016) showed that FRAM in its original format is unable to explore the paths of hazards, so it has to be combined with other approaches to address the issues of complex socio-technical systems.

Table 2.5: Methods[9] used in the analyzed studies.

Study	Methods/models/approaches																				
	FRAM	System performance measurement	Mathematical modeling	Human factors	Analytic hierarchy process	statistical methods	Joint cognitive system	24 model	ACAT	Simulation	Lean production	Simple Promela Interpreter	Abstraction hierarchy	Anticipatory Failure Determination	Bayesian Networks	Fault tree	CREAM	Model checking	Variation tree analysis	Grounded theory	STEP
Buikstra et al. (2020)	✓																				
Smith et al. (2020)	✓	✓																			
Yu et al. (2020)	✓		✓																		
O'Hara et al. (2020)	✓																				
Lee et al. (2019)	✓			✓																	
Ferreira & Cañas (2019)	✓																				
França et al. (2019)	✓				✓																
Gao et al. (2019)	✓					✓															
Damen et al. (2019)	✓																				
Schutijser et al. (2019)	✓																				
Adriaensen et al. (2019)	✓						✓														

[9] Models and approaches were also investigated in the analyzed studies.

Huang et al. (2019)	✓							✓													
Kaya et al. (2019)	✓																				
Li et al. (2019)	✓								✓												
Patriarca et al. (2018)	✓									✓											
Rosso & Saurin (2018)	✓										✓										
Wachs & Saurin (2018)	✓																				
McNab et al. (2018)	✓																				
Raben, Bogh, et al. (2018)	✓																				
Bridges et al. (2018)	✓																				
Raben, Viskum, et al. (2018)	✓																				
Ross et al. (2018)	✓					✓															
Lee & Chung (2018)	✓			✓																	
Smith et al. (2018)	✓																				
Wachs et al. (2018)	✓																				
Patriarca, Di Gravio, Costantino, et al. (2017)	✓									✓											
Yang et al. (2017)	✓											✓									
Patriarca & Bergström (2017)	✓												✓								
Pickup et al. (2017)	✓			✓																	
Jensen & Aven (2017)	✓													✓							
Anvarifar et al. (2017)	✓																				

Studic et al. (2017)	✓																			✓	
Patriarca, Bergström, et al. (2017)	✓												✓								
Patriarca, Di Gravio, & Costantino (2017)	✓									✓											
de Vries (2017)	✓																				
Saurin & Werle (2017)	✓					✓															
Smith et al. (2017)	✓														✓	✓					
Furniss et al. (2016)	✓																				
Hirose et al. (2016)	✓																✓				
Zheng et al. (2016)	✓																				
Aguilera et al. (2016)	✓																				
Tian et al. (2016)	✓																	✓			
Toroody et al. (2016)	✓															✓					
Fukuda et al. (2016)	✓																		✓		
Duan et al. (2015)	✓																	✓			
Praetorius et al. (2015)	✓																				
Rosa et al. (2015)	✓				✓																
Clay-Williams et al. (2015)	✓																				
Laugaland et al. (2014)	✓																				
De Carvalho (2011)	✓																				
Belmonte et al. (2011)	✓									✓						✓					

Herrera & Woltjer (2010)	✓																				✓

2.4. Discussion

2.4.1. FRAM as a basis for managing safety, accident, risk, and complexity

There has been considerable growth in employing FRAM for safety management related purposes. FRAM is capable of finding appropriate solutions for maintaining work operations in an acceptable boundary of safety, as highlighted by Hulme et al. (2019). This may be due to the unique characteristic of FRAM in monitoring complex systems for identifying variabilities and managing them, rather than looking for human error or root causes of adverse events, as highlighted by Accou & Reniers (2019). The capability of FRAM in recognizing the sources of variability is crucial for safety management as functions can be coupled and lead to unexpected outcomes (Grant et al., 2018; Hollnagel, 2012b). In other words, small variations in functions can impact the dynamics of complex socio-technical systems and influence the safety of the systems. FRAM can be used for safety-related investigations, and for proposing safety measures by monitoring and managing variability aggregated over different functions of a system, as Tian et al. (2016) pointed out. The role of FRAM is also emphasized in patient safety management. This could be because FRAM is capable of effective functional resonance management in complex operations and processes that can result in improving patients' safety and health, as highlighted by Buikstra et al. (2020) and O'Hara et al. (2020).

FRAM can also be used for accident/incident investigations, as Hulme et al. (2019) and Shire et al. (2018) pointed out. It simply means that FRAM facilitates the process of analyzing something that has happened (retrospective analysis) (Huang et al., 2019). From the FRAM perspective, accidents can result from unexpected combinations (resonances) of the variability of action or behavior. Therefore, accidents can be avoided by monitoring and reducing variability, as Alvarenga et al. (2014) emphasized. A wide range of factors, including technical, human, and organizational factors can be incorporated when FRAM is used to analyze accidents, incidents, or events. Identifying and adding barriers to functions for preventing accidents/incidents is another capability of FRAM, as highlighted by Huang et al. (2019), Yang et al. (2017), and Patriarca, Di Gravio, & Costantino (2017).

FRAM could potentially be applied in studies associated with hazard identification and risk management. The aims of the studies might include looking at something that may happen in the future to identify possible hazards (prospective analysis). Risk analysts must pay attention to the dynamics of the whole system and not just to the action or behavior of the individual parts, as Alvarenga et al. (2014) highlighted. FRAM might help model complex interactions and performance variability that contribute to potential hazards. Proactive FRAM-based frameworks could be developed to identify operational risks in complex operations. They might contribute to risk management by recognizing functions and dynamic couplings among them, as Li et al. (2019) mentioned. The key role of FRAM in hazard identification is highlighted in several studies (Fukuda et al., 2016; Jensen & Aven, 2017; Rosa et al., 2015; Saurin & Werle, 2017).

Employing FRAM for managing complexity in socio-technical systems is recommended by Patriarca & Bergström (2017). One justification is the capability of

FRAM for describing and analyzing interdependencies among system elements or functions. Unlike most conventional safety management methods that do not consider human and organizational factors (Hollnagel, 2016; Woods & Cook, 2002), FRAM considers technological, human, and organizational functions together (Hollnagel, 2012b). Moreover, it includes external/environmental factors. The role of FRAM is not limited to identifying the functions of a system; it is able to describe the dynamic interactions among functions, as Duan et al. (2015) and França et al. (2019) highlighted. It can be helpful in visualizing the complexity of socio-technical systems' processes (De Carvalho, 2011; de Vries, 2017; Kaya et al., 2019). FRAM plays a vital role in understanding complex systems. When complexity increases, managing complexity becomes more important, and FRAM becomes more valuable (Hollnagel, 2012a; Ragosta et al., 2015; Toroody et al., 2016) because it can be helpful in providing a functional description of systems and allowing a transparent analysis.

2.4.2. A wide spectrum of domains in practice

FRAM is usable in a wide range of domains/contexts, as revealed by the results of the current review. The most widely used domains were healthcare, aviation, maritime, and railway. Similarly, Hulme et al. (2019) showed that aviation, maritime, railway, and healthcare were the most common domains that hosted systemic approaches, such as FRAM, AcciMap, the Human Factors Analysis and Classification System (HFACS), and the Systems Theoretic Accident Model and Processes (STAMP). The domains are known for their complexity and risky environments. Although other domains, such as process industries, industrial processes, and the power industry are also hazardous and complex, the use of FRAM in those domains was less common.

Healthcare was the domain where FRAM was employed more than any other domain. It is also the most common domain that hosted other systemic approaches, such as AcciMapp (Hulme et al., 2019) and system dynamics (Shire et al., 2018). The reason why FRAM has been used most often in healthcare may be due to the nature and structure of the healthcare sector, as pointed out by Shire et al. (2018). It is more a social system than an engineered system. In healthcare, frontline personnel must adapt to work conditions where preconditions are not ideal and resources are limited (Hounsgaard, 2016).

Aviation was another main domain to which FRAM has been applied, as Pardo-Ferreira et al. (2019) confirmed. It has also been the most common domain for other systemic approaches, such as the HFACS (Hulme et al., 2019). FRAM might provide relevant support to address critical issues in aviation focusing on accident analysis (Arie Adriaensen et al., 2019). One possible reason could be the complexity of aviation related problems, which requires a systemic modelling method, rather than one that concentrates on accident/incident investigation, as Stogsdill & Ulfvengren (2017) highlighted.

2.4.3. A mixed method for developing and validating a FRAM model

A mixed method of data collection approaches must be used to develop and validate FRAM models. The data required for developing a FRAM model must be provided by multiple sources and different methods. Interviews, the most popular approach, can be employed to obtain data required for developing a FRAM model. One possible reason for the popularity of interviews is that it is a face to face approach and might be helpful in gaining more details for identifying functions, their aspects, and their descriptions, as Bridges et al. (2018) and Settanni et al. (2017) highlighted. Observation is another useful technique for developing a FRAM model because it enables a deeper insight into complex systems and their procedures, as emphasized by Kaya et al. (2019) and Wachs & Saurin (2018).

Official accident/incident investigation reports can be used as a major source to map and model complex socio-technical systems, particularly in aviation-related studies. The majority of the studies in the aviation sector aim to understand and analyze accidents, incidents, or events that happened in the past (Duan et al., 2015; Hirose et al., 2016; Yang et al., 2017). They require a retrospective-based method and can employ FRAM for retrospective analysis, as (Dallat et al., 2017) emphasized. Hence, using official reports associated with accidents and incidents is the most likely option for building a FRAM model in aviation-related analyses. An integration of different approaches (such as interview, observation, focus group, and document analysis) would be the best way of data collection for constructing a FRAM model in the healthcare sector, as highlighted by a number of studies (Patriarca et al., 2018; Rosso & Saurin, 2018; Schutijser et al., 2019). The major reason could be the multi-dimensional nature of healthcare where organizational, human, and technological dimensions are involved. Therefore, multiple sources can cover more dimensions and increase the comprehensiveness of the developed model.

Model validation is of great importance as it increases the reliability of the developed FRAM models. Interviews with experts, workshops, and discussions may be the most important ways for validating developed models, as pointed out by Bridges et al.

(2018), Kaya et al. (2019), and Ross et al. (2018). The reason may be associated with experts' deep knowledge about normal work, work systems, and daily operations. Such knowledge can be helpful for enriching developed FRAM models and providing more reliable models.

2.4.4. Addressing deficiencies for better use

FRAM has remarkable capabilities, though there are some deficiencies that should be addressed to enhance its performance in modeling complex socio-technical systems for improving safety and risk management. Suggestions to address some of the deficiencies are discussed here. One main challenge was that there is no consensus on how much information is required to describe a function. Employing complementary approaches can be useful to provide a more comprehensive description of functions in FRAM. To this end, employing approaches, such as the Accident Causation Analysis and Taxonomy (ACAT) and Rasmussen's Abstraction Hierarchy (AH), could improve the comprehensibility of FRAM models, as highlighted by Li et al. (2019) and Patriarca, Bergström, et al. (2017). The next problem is that the degree of understandability of a FRAM model decreases as the number of functions encompassed by it increases. One solution could be the use of graph-based methods to construct a more understandable model, encompassing start and end points, as Toroody et al. (2016) acknowledged. Another deficiency of FRAM was associated with identifying hazard paths. To this end, model checking could be employed to address the deficiency. Using the model checking might enable FRAM-based models to identify the paths of hazards in complex socio-technical systems, as pointed out by Duan et al. (2015), Tian et al. (2016), and Zheng et al. (2016).

Lastly, this review suggests employing supplementary approaches to improve the deficiencies of FRAM, particularly the computational facet, including performance variability. This means concentration on creating a bridge between FRAM and other (quantitative) approaches could be helpful. Using multi-layer approaches, like Monte Carlo simulation might be helpful to quantify the sources of variability in complex systems, as Falegnami et al. (2019) and Patriarca, Di Gravio, & Costantino (2017) highlighted. The analytic hierarchy process (AHP) method might be another solution for identifying the sources of performance variability and finding functional resonance by investigating the relative importance of criteria and alternatives (Rosa et al., 2015). An integration of mathematical-simulation related solutions might be useful to overcome the restrictions of FRAM. The principles of simulation and rule mining could be applied to compute the aggregation of variability and identify the influence of interactions among upstream functions affecting downstream functions (Yu et al., 2020).

2.5. Study limitations and future research directions

The current review suffered from one limitation that should be mentioned. The process of article selection was narrowly defined to include only peer reviewed journal articles. Books, conference papers, and technical reports were excluded from the analysis. Some of the excluded studies could add some value to the analysis performed in the current review.

The evolution of FRAM is of great importance for future research. Constructing a FRAM model is still time consuming. Developing (semi-)automatic data collection approaches, including function identification and aspect specification, could be helpful in saving time for building models. Method(s) for quantifying variability should also be developed in terms of (at least) time and precision. Different attempts have not resulted in a formal quantitative approach for calculating variability yet, although research interest has grown in this regard, as exemplified by the use of fuzzy logic (Hirose & Sawaragi, 2020) and the concept of functional signatures (Smith et al., 2020).

2.6. Conclusions

This review paper has reported and analyzed published studies that use FRAM. A total of 52 studies were included in the review. The application of the FRAM approach has increased during this decade. It has been employed in a wide spectrum of complex socio-technical system domains. This review purposefully aimed to address four research questions. In this regard, the following key findings are presented. First, the focus of the investigated studies was on safety management, accident/incident investigation, hazard identification/risk management, and complexity management in complex socio-technical systems. As complexity and variability are systemic problems, a holistic approach is required to handle them. The results presented in this review indicated that FRAM is capable of addressing the problems by investigating technological, human, organizational, and other external factors affecting complex systems' boundaries. Second, a wide range of domains employed FRAM to analyze complex socio-technical systems and recognize barriers for safety enhancement. The results showed that healthcare, aviation, maritime, and railway were the most popular domains for applying FRAM. The third finding of this review is related to data collection approaches. According to the results, interview, observation, and reports/documents analysis are the most common approaches to build a FRAM model. A compilation of the mentioned approaches could assist analysts to employ FRAM in a more comprehensive way. The last finding reveals flaws of FRAM in practice. Despite several advantages for modeling complex systems and safety improvement, it has a few deficiencies. There is a clear need for exploring further research opportunities to address the flaws and deficiencies around FRAM to satisfy the safety-related demands of complex socio-technical systems.

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References

Accou, B., & Reniers, G. (2019). Developing a method to improve safety management systems based on accident investigations: the SAfety FRactal ANalysis. *Safety Science*, *115*, 285–293.

Adriaensen, A., Patriarca, R., Smoker, A., & Bergström, J. (2019). A socio-technical analysis of functional properties in a joint cognitive system: a case study in an aircraft cockpit. *Ergonomics*, *just-accepted*, 1–48.

Aguilera, M. V. C., da Fonseca, B. B., Ferris, T. K., Vidal, M. C. R., & de Carvalho, P. V. R. (2016). Modelling performance variabilities in oil spill response to improve system resilience. *Journal of Loss Prevention in the Process Industries*, *41*, 18–30.

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.

Alvarenga, M. A. B., e Melo, P. F. F., & Fonseca, R. A. (2014). A critical review of methods and models for evaluating organizational factors in Human Reliability Analysis. *Progress in Nuclear Energy*, *75*, 25–41.

Anvarifar, F., Voorendt, M. Z., Zevenbergen, C., & Thissen, W. (2017). An application of the Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood defences in the Netherlands. *Reliability Engineering & System Safety*, *158*, 130–141.

Belmonte, F., Schön, W., Heurley, L., & Capel, R. (2011). Interdisciplinary safety analysis of complex socio-technological systems based on the functional resonance accident model: An application to railway trafficsupervision. *Reliability Engineering & System Safety*, *96*(2), 237–249.

Bergström, J., Van Winsen, R., & Henriqson, E. (2015). On the rationale of resilience in the domain of safety: A literature review. *Reliability Engineering & System Safety*, *141*, 131–141.

Bjerga, T., Aven, T., & Zio, E. (2016). Uncertainty treatment in risk analysis of complex systems: The cases of STAMP and FRAM. *Reliability Engineering & System Safety*, *156*, 203–209.

Bridges, K. E., Corballis, P. M., & Hollnagel, E. (2018). "Failure-to-Identify" Hunting Incidents: A Resilience Engineering Approach. *Human Factors*, *60*(2), 141–159.

Buikstra, E., Strivens, E., & Clay-Williams, R. (2020). Understanding variability in discharge planning processes for the older person. *Safety Science*, *121*, 137–146.

Clay-Williams, R., Hounsgaard, J., & Hollnagel, E. (2015). Where the rubber meets the road: using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines. *Implementation Science*, *10*(1), 125.

Costantino, F., Di Gravio, G., & Tronci, M. (2018). Environmental Audit improvements in industrial systems through FRAM. *IFAC-PapersOnLine*, *51*(11), 1155–1161.

Dallat, C., Salmon, P. M., & Goode, N. (2017). Risky systems versus risky people: To what extent do risk assessment methods consider the systems approach to accident causation? A review of the literature. *Safety Science*.

Damen, N. L., de Vos, M. S., Moesker, M. J., Braithwaite, J., van Wijngaarden, R. A. F. de L., Kaplan, J., Hamming, J. F., & Clay-Williams, R. (2019). Preoperative anticoagulation management in everyday clinical practice: an international comparative analysis of work-as-done using the functional resonance analysis method. *Journal of Patient Safety,* 17(3), 157-165.

De Carvalho, P. V. R. (2011). The use of Functional Resonance Analysis Method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience. *Reliability Engineering & System Safety*, *96*(11), 1482–1498.

de Vries, L. (2017). Work as done? Understanding the practice of sociotechnical work in the maritime domain. *Journal of Cognitive Engineering and Decision Making*, *11*(3), 270–295.

Dekker, S., Cilliers, P., & Hofmeyr, J.-H. (2011). The complexity of failure: implications of complexity theory for safety investigations. *Safety Science*, *49*(6), 939–945.

Duan, G., Tian, J., & Wu, J. (2015). Extended FRAM by integrating with model checking to effectively explore hazard evolution. *Mathematical Problems in Engineering*, *2015*.

Falegnami, A., Costantino, F., Di Gravio, G., & Patriarca, R. (2019). Unveil key functions in socio-technical systems: mapping FRAM into a multilayer network. *Cognition, Technology & Work*, 1–23.

Ferreira, P. N. P., & Cañas, J. J. (2019). Assessing operational impacts of automation using functional resonance analysis method. *Cognition, Technology & Work*, 1–18.

França, J. E. M., Hollnagel, E., dos Santos, I. J. A. L., & Haddad, A. N. (2019). FRAM AHP approach to analyse offshore oil well drilling and construction focused on human factors. *Cognition, Technology & Work*, 1–13.

Fukuda, K., Sawaragi, T., Horiguchi, Y., & Nakanishi, H. (2016). Applying systemic accident model to learn from near-miss incidents of train maneuvering and operation. *IFAC-PapersOnLine*, *49*(19), 543–548.

Furniss, D., Curzon, P., & Blandford, A. (2016). Using FRAM beyond safety: a case study to explore how sociotechnical systems can flourish or stall. *Theoretical Issues in Ergonomics Science*, *17*(5–6), 507–532.

Gao, Y., Fan, Y., Wang, J., & Duan, Z. (2019). Evaluation of governmental safety regulatory functions in preventing major accidents in China. *Safety Science*, *120*, 299–311.

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.

Grant, E., Salmon, P. M., Stevens, N. J., Goode, N., & Read, G. J. (2018). Back to the future: What do accident causation models tell us about accident prediction? *Safety Science*, *104*, 99–109.

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.

Hill, R., & Hollnagel, E. (2016). *Instructions for use of the FRAM Model Visuliser (FMV)*.

Hirose, T., & Sawaragi, T. (2020). Extended FRAM model based on cellular automaton to clarify complexity of socio-technical systems and improve their safety. *Safety Science*, *123*, 104556.

Hirose, T., Sawaragi, T., & Horiguchi, Y. (2016). Safety analysis of aviation flight-deck procedures using systemic accident model. *IFAC-PapersOnLine*, *49*(19), 19–24.

Hollnagel, E. (2012a). Coping with complexity: past, present and future. *Cognition, Technology & Work*, *14*(3), 199–205.

Hollnagel, E. (2012b). *FRAM, the functional resonance analysis method: modelling complex socio-technical systems*. Ashgate Publishing, Ltd.

Hollnagel, E. (2016). *Barriers and accident prevention*. Routledge.

Hollnagel, E. (2017). *FRAM: the functional resonance analysis method: modelling complex socio-technical systems*. CRC Press.

Hollnagel, E. (2018). *Safety-I and safety-II: the past and future of safety management*. CRC press.

Hounsgaard, J. (2016). *Patient Safety in Everyday Work: Learning from things that go right*. Syddansk Universitet.

Huang, W., Shuai, B., Zuo, B., Xu, Y., & Antwi, E. (2019). A systematic railway dangerous goods transportation system risk analysis approach: The 24 model. *Journal of Loss Prevention in the Process Industries*.

Hulme, A., Stanton, N. A., Walker, G. H., Waterson, P., & Salmon, P. M. (2019). What do applications of systems thinking accident analysis methods tell us about accident causation? A systematic review of applications between 1990 and 2018. *Safety Science*, *117*, 164–183.

Jensen, A., & Aven, T. (2017). Hazard/threat identification: Using functional resonance analysis method in conjunction with the Anticipatory Failure Determination method. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *231*(4), 383–389.

Jensen, A., & Aven, T. (2018). A new definition of complexity in a risk analysis setting. *Reliability Engineering & System Safety*, *171*, 169–173.

Kaya, G. K., Ovali, H. F., & Ozturk, F. (2019). Using the functional resonance analysis method on the drug administration process to assess performance variability. *Safety Science*, *118*, 835–840.

Laugaland, K., Aase, K., & Waring, J. (2014). Hospital discharge of the elderly-an observational case study of functions, variability and performance-shaping factors. *BMC Health Services Research*, *14*(1), 365.

Lee, J., & Chung, H. (2018). A new methodology for accident analysis with human and system interaction based on FRAM: Case studies in maritime domain. *Safety Science*, *109*, 57–66.

Lee, J., Yoon, W. C., & Chung, H. (2019). Formal or informal human collaboration approach to maritime safety using FRAM. *Cognition, Technology & Work*, 1–15.

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

Li, W., He, M., Sun, Y., & Cao, Q. (2019). A proactive operational risk identification and analysis framework based on the integration of ACAT and FRAM. *Reliability Engineering & System Safety*, *186*, 101–109.

McNab, D., Freestone, J., Black, C., Carson-Stevens, A., & Bowie, P. (2018). Participatory design of an improvement intervention for the primary care management of possible sepsis using the Functional Resonance Analysis Method. *BMC Medicine*, *16*(1), 174.

Moorkamp, M., Kramer, E.-H., Van Gulijk, C., & Ale, B. (2014). Safety management theory and the expeditionary organization: A critical theoretical reflection. *Safety Science*, *69*, 71–81.

O'Hara, J. K., Baxter, R., & Hardicre, N. (2020). 'Handing over to the patient': A FRAM analysis of transitional care combining multiple stakeholder perspectives. *Applied Ergonomics*, *85*, 103060.

Pardo-Ferreira, M. C., Martínez-Rojas, M., Salguero-Caparrós, F., & Rubio-Romero, J. C. (2019). Evolution of the Functional Resonance Analysis Method (FRAM) through the combination with other methods. *Dirección y Organización*, 41–50.

Patriarca, R., & Bergström, J. (2017). Modelling complexity in everyday operations: functional resonance in maritime mooring at quay. *Cognition, Technology &*

Work, *19*(4), 711–729.

Patriarca, R., Bergström, J., & Di Gravio, G. (2017). Defining the functional resonance analysis space: Combining Abstraction Hierarchy and FRAM. *Reliability Engineering & System Safety*, *165*, 34–46.

Patriarca, R., Di Gravio, G., & Costantino, F. (2017). A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. *Safety Science*, *91*, 49–60.

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.

Patriarca, R., Falegnami, A., Costantino, F., & Bilotta, F. (2018). Resilience engineering for socio-technical risk analysis: Application in neuro-surgery. *Reliability Engineering & System Safety*, *180*, 321–335.

Patriarca, R., Gianluca, D.P., Giulio, D.G. and Francesco, C., 2018. FRAM for systemic accident analysis: a matrix representation of functional resonance. International Journal of Reliability, Quality and Safety Engineering, 25(01), p.1850001.

Pereira, A. G. (2013). *Introduction to the Use of FRAM on the effectiveness assessment of a radiopharmaceutical Dispatches process*.

Pickup, L., Atkinson, S., Hollnagel, E., Bowie, P., Gray, S., Rawlinson, S., & Forrester, K. (2017). Blood sampling-Two sides to the story. *Applied Ergonomics*, *59*, 234–242.

Praetorius, G., Graziano, A., Schröder-Hinrichs, J.-U., & Baldauf, M. (2017). Fram in FSA—Introducing a function-based approach to the formal safety assessment framework. In *Advances in Human Aspects of Transportation* (pp. 399–411). Springer.

Praetorius, G., Hollnagel, E., & Dahlman, J. (2015). Modelling Vessel Traffic Service to understand resilience in everyday operations. *Reliability Engineering & System Safety*, *141*, 10–21.

Raben, D. C., Bogh, S. B., Viskum, B., Mikkelsen, K. L., & Hollnagel, E. (2018). Learn from what goes right: A demonstration of a new systematic method for identification of leading indicators in healthcare. *Reliability Engineering & System Safety*, *169*, 187–198.

Raben, D. C., Viskum, B., Mikkelsen, K. L., Hounsgaard, J., Bogh, S. B., & Hollnagel, E. (2018). Application of a non-linear model to understand healthcare processes: using the functional resonance analysis method on a case study of the early detection of sepsis. *Reliability Engineering & System Safety*, *177*, 1–11.

Ragosta, M., Martinie, C., Palanque, P., Navarre, D., & Sujan, M. A. (2015). Concept maps for integrating modeling techniques for the analysis and re-design of partly-autonomous interactive systems. *Proceedings of the 5th International Conference on Application and Theory of Automation in Command and Control Systems*, 41–52.

Righi, A. W., & Saurin, T. A. (2015). Complex socio-technical systems: Characterization and management guidelines. *Applied Ergonomics*, *50*, 19–30.

Roland, D. (2018). Guideline developers are not the only experts: Utilising the FRAM method in sepsis pathways. *BMC Medicine*, *16*(1), 213.

Rosa, L. V., Haddad, A. N., & de Carvalho, P. V. R. (2015). Assessing risk in sustainable construction using the Functional Resonance Analysis Method (FRAM). *Cognition, Technology & Work*, *17*(4), 559–573.

Ross, A., Sherriff, A., Kidd, J., Gnich, W., Anderson, J., Deas, L., & Macpherson, L. (2018). A systems approach using the functional resonance analysis method to support fluoride varnish application for children attending general dental practice. *Applied Ergonomics*, *68*, 294–303.

Rosso, C. B., & Saurin, T. A. (2018). The joint use of resilience engineering and lean production for work system design: a study in healthcare. *Applied Ergonomics*, *71*, 45–56.

Saurin, T. A., & Werle, N. J. B. (2017). A framework for the analysis of slack in socio-technical systems. *Reliability Engineering & System Safety*, *167*, 439–451.

Schutijser, B. C. F. M., Jongerden, I. P., Klopotowska, J. E., Portegijs, S., de Bruijne, M. C., & Wagner, C. (2019). Double checking injectable medication administration: Does the protocol fit clinical practice? *Safety Science*, *118*, 853–860.

Settanni, E., Thenent, N. E., Newnes, L. B., Parry, G., & Goh, Y. M. (2017). Mapping a product-service-system delivering defence avionics availability. *International Journal of Production Economics*, *186*, 21–32.

Shire, M. I., Jun, G. T., & Robinson, S. (2018). The application of system dynamics modelling to system safety improvement: Present use and future potential. *Safety Science*, *106*, 104–120.

Smith, D., Veitch, B., Khan, F., & Taylor, R. (2018a). Using FRAM to evaluate ship designs and regulations. In *Marine Design XIII, Volume 2* (pp. 677–683). CRC Press.

Smith, D., Veitch, B., Khan, F., & Taylor, R. (2018b). Using the FRAM to Understand Arctic Ship Navigation: Assessing Work Processes During the Exxon Valdez Grounding. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, *12*.

Smith, D., Veitch, B., Khan, F., & Taylor, R. (2017). Understanding industrial safety: Comparing Fault tree, Bayesian network, and FRAM approaches. *Journal of Loss Prevention in the Process Industries*, *45*, 88–101.

Smith, D., Veitch, B., Khan, F., & Taylor, R. (2020). Integration of Resilience and FRAM for Safety Management. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *6*(2), 4020008.

Soliman, M., & Saurin, T. A. (2017). Lean production in complex socio-technical systems: a systematic literature review. *Journal of Manufacturing Systems*, *45*, 135–148.

Stanton, N. A., Salmon, P. M., Walker, G. H., & Stanton, M. (2019). Models and methods for collision analysis: A comparison study based on the Uber collision with a pedestrian. *Safety Science*, *120*, 117–128.

Stogsdill, M., & Ulfvengren, P. (2017). Mapping risk models/methods onto a complexity spectrum. *Transportation Research Procedia*, *28*, 133–140.

Studic, M., Majumdar, A., Schuster, W., & Ochieng, W. Y. (2017). A systemic modelling of ground handling services using the functional resonance analysis method. *Transportation Research Part C: Emerging Technologies*, *74*, 245–260.

Tian, J., Wu, J., Yang, Q., & Zhao, T. (2016). FRAMA: a safety assessment approach based on Functional Resonance Analysis Method. *Safety Science*, *85*, 41–52.

Toroody, A. B., Abaei, M. M., & Gholamnia, R. (2016). Conceptual compression discussion on a multi-linear (FTA) and systematic (FRAM) method in an offshore operation's accident modeling. *International Journal of Occupational Safety and Ergonomics*, *22*(4), 532–540.

Wachs, P., Righi, A. W., & Saurin, T. A. (2018). The Functional Resonance Analysis Method as a Debriefing Tool in Scenario-Based-Training. *Congress of the International Ergonomics Association*, 132–138.

Wachs, P., & Saurin, T. A. (2018). Modelling interactions between procedures and resilience skills. *Applied Ergonomics*, *68*, 328–337.

Woods, D. D., & Cook, R. I. (2002). Nine steps to move forward from error. *Cognition, Technology & Work*, *4*(2), 137–144.

Yang, Q., Tian, J., & Zhao, T. (2017). Safety is an emergent property: Illustrating functional resonance in Air Traffic Management with formal verification. *Safety Science*, *93*, 162–177.

Yu, M., Quddus, N., Kravaris, C., & Mannan, M. S. (2020). Development of a FRAM-based framework to identify hazards in a complex system. *Journal of Loss Prevention in the Process Industries*, *63*, 103994.

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.

Chapter 3

A dynamic version of the FRAM for capturing variability in complex operations*

Co-authorship statement. A version of this chapter has appeared as an article in the journal titled *MethodsX* published by *Elsevier*. The lead author, Vahid Salehi, has developed and examined the FRAM model in healthcare context. He also extracted the empirical data using documents review. The co-author Dr. Doug Smith has developed the DynaFRAM software and contributed to shaping the interview questions to get the data we used to build the model. The co-author Natasha Hanson led the data collection process for gathering the data related to frail older patients. Co-authors Prof. Brian Veitch and Dr. Doug Smith supervised the study. All authors read and approved the final draft.

Abstract. Functional Resonance Analysis Method (FRAM) is a function-based approach to model complex socio-technical systems and to manage variability. The current FRAM related tools are unable to capture qualitative and quantitative characteristics of variability as well as temporal variations. This study presents in detail a dynamic FRAM-based tool, which is called DynaFRAM. It is introduced to address the variability-related deficiencies of the FRAM related tools. It aims to capture variability in complex operations. It is a dynamic tool developed to capture

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time related variations in complex operations. This increases the attractiveness of the DynaFRAM for complex operations where specialists and practitioners make decisions in complicated situations. The ability of the DynaFRAM is demonstrated by examining a healthcare related case study. Although the ability of the DynaFRAM is assessed through capturing variations in healthcare operations, it can be applied to other domains in a similar manner.

Keywords: Variability; Temporal variations; Instantiation; Healthcare operations.

3.1. Introduction

Functional resonance analysis method (FRAM), developed by Hollnagel (2012b), is a method that provides the possibility of constructing a functional model, including two major parameters: functions and variability. Mapping functions helps explain the potential functional pathways in an operation and understand the connectivity of the work in the operation (Smith et al., 2020). The concept of variability emphasizes that the nature of the outputs of functions is variable (Raben, Viskum, et al., 2018). Modelling socio-technical systems in terms of functions and variability provides valuable insights that can be helpful in safety management of complex operations (Patriarca & Bergström, 2017).

Variability is deviations observed in the outputs of functions or the outcomes of the entire system (Hollnagel, 2012b; Tian et al., 2016). It represents a normal, essential part of work and reflects the need to cope with unstable working conditions (Hollnagel, 2012b). The variability and adjustments of a function can affect other functions and thereby the activity as a whole. Functions can mutually dampen each other (absorb variability), so that the situation can become stabilized. They can also mutually reinforce each other (amplify variability) so that the situation becomes unstable and leads to unexpected and usually unwanted results (Hollnagel, 2012b). Therefore, variability can lead both to positive (successful) and negative (unsuccessful) outcomes (Hollnagel, 2012b; Patriarca, Di Gravio, & Costantino, 2017a).

The FRAM has been widely used for pursuing different purposes in various fields, such as healthcare, aviation, maritime, railway, environment, and process industries (Salehi et al., 2020). According to Ransolin et al. (2020), the FRAM can provide a basis for modelling functional requirements and supporting resilient performance analysis in an intensive care unit (ICU) within the healthcare sector. It can also help understand the influences of information propagation and take advantage of functional properties in the cockpit environment of an aircraft (Arie Adriaensen et al., 2019). It also has been applied to maritime activities according to de Vries (2017). FRAM has been combined with other methods to address industrial problems. Li et al. (2019) employed the FRAM with the Accident Causation Analysis and Taxonomy (ACAT), introducing a framework for identifying and analyzing operational risks. Studic et al. (2017) introduced a framework based on FRAM and grounded theory for improving the safety management of ground handling services.

Despite the wide application of the FRAM in different disciplines and its central role in functional analyses, it suffers from capturing and visualizing the variability of functions (Aguilera et al., 2016; Anvarifar et al., 2017; Patriarca, Di Gravio, & Costantino, 2017a; Praetorius et al., 2017). Capturing variability is of great importance as the variability of coupled functions can amplify each other and result in unwanted outcomes and serious accidents (Hollnagel, 2012b). There are a few tools to support the FRAM method: FRAM Model Visualiser (FMV) software developed by Hill & Hollnagel (2016), FRAM Model Interpreter (FMI) developed by Hollnagel (2021), and myFRAM developed by Patriarca, Di Gravio, & Costantino (2017b) are three well-known examples of FRAM related tools. The characteristics of the tools are presented in Table 3.1. The FMV software is a powerful tool to model complex socio-technical systems (Hill & Hollnagel, 2016). The FMI is used to interpret a built FRAM model and help determine how an explained activity or task may develop (Hollnagel, 2021). The myFRAM is another powerful tool developed to support the constructing process of a FRAM model (Patriarca, Di Gravio, & Costantino, 2017b). As shown in Table 3.1, the three developed tools provide some support to model complex socio-technical systems and interpret the constructed models. The focus of the tools is not on capturing and visualizing variability, although performance variability is a key principle of the FRAM method (Shirali & Ebrahipour, 2013; Woltjer & Hollnagel, 2008). The DynaFRAM is introduced to help understand variability in complex operations. It provides a way of visualizing and understanding qualitative and quantitative characteristics of functional variability. It is also able to visualize performance variability for different cases. Additionally, it is capable of characterizing variations related to instantiations or functional pathways that produce the outcome(s) of the entire system. Moreover, it is able to capture temporal variations related to functions and the entire system. An instantiation characterizes how many functions and which functions are involved in the pathway that each case takes. In this study, an instantiation refers to the experience of a frail patient during transition from hospital to home.

Table 3.1: The characteristics of DynaFRAM versus other tools.

	Modelling	Interpretation	Variability	Dynamic
DynaFRAM			✓	✓
FRAM Model Visualizer (FMV) (Hill & Hollnagel, 2016)	✓			
FRAM Model Interpreter (FMI) (Hollnagel, 2021)		✓		
myFRAM (Patriarca, Di Gravio, & Costantino, 2017b)	✓			

The main objective of this study is to introduce a dynamic FRAM-based tool with the purpose of capturing different characteristics of variability, in order to provide adequate support for the analysis and management of complex operations. The dynamic FRAM-based tool presented in this study can be effective in three ways: (i) capturing and visualizing the qualitative characteristic of variability of functional outputs and instantiations/pathways that produce outcome(s) of the entire system; (ii) capturing the quantitative characteristic of functional variability; and (iii) capturing temporal variations regarding both functions and instantiations.

3.2. Methodology

3.2.1. Functional Resonance Analysis Method (FRAM)

The FRAM includes four steps. The first step is to identify functions of the system under study and to describe the functions based on their aspects (Hollnagel, 2012b). Each function can have six aspects as follows:

- **Input (I):** something that starts a function.
- **Output (O):** it is the outcome(s) or result(s) of a function. When a function is carried out, outputs are produced. The outputs can influence the outputs of other functions in maximum five different ways (input, precondition, resource, control, and time).
- **Preconditions (P):** conditions that must be met before a function begins. Preconditions do not start a function.
- **Resources (R):** what a function consumes or requires for producing an output or outputs.
- **Time (T):** temporal restrictions that influence a function (starting time, finishing time, and duration).
- **Control (C):** that monitors or regulates a function.

After identifying functions and describing their aspects, the variability should be captured and characterized (Hollnagel, 2012b). It refers to the variety of ways that the output(s) of a function can be produced (step 2). The third step is to show the aggregation of variability (functional resonance). It refers to variations related to coupled functions. The variability of upstream functions can influence downstream functions, and the whole system performance can be affected as a result (Smith et al., 2020) . The fourth and final step is associated with identifying the proper approaches for monitoring the system, controlling its variability, and suggesting possible safety barriers (Hollnagel, 2012b). It is noteworthy that the FMV software was developed to model complex socio-technical systems (Hill & Hollnagel, 2016).

3.2.2. DynaFRAM: A dynamic FRAM-based tool

A dynamic FRAM-based tool, called DynaFRAM, was developed through programming in the Python programming language. It was developed to cover the variability-related deficiencies of the FRAM related tools described in the Background section. The DynaFRAM tool allows capturing and visualizing variations that occur both in the outputs of functions and in the outcome(s) of the entire system. The DynaFRAM aims to visualize what is produced at the end of a function, when it occurs, and for how long it occurs. Another advantage of developing the DynaFRAM is to provide more flexibility for users to generate scenarios and capture temporal variations both in the outputs of functions and in the outcome(s) of the entire system. The DynaFRAM is able to capture and visualize functional outputs at a specific period of time when operations are performed. Recording instantiations of variability is possible with the DynaFRAM if the data of more samples are collected in real operations (work-as-observed). A general view of the DynaFRAM tool is illustrated in Figure 3.3.

Pseudo-codes presented in Figures 3.1 and 3.2 show how to capture time for an instantiation. The pseudo-code shown in Figure 3.1 is for uploading a FRAM model and starting video recording for capturing the time of an instantiation. First, it is checked to ensure a model is uploaded. Then, a class is called to calculate time by a timer. Time is recorded for an instantiation through the pseudo-code presented in Figure 3.2.

```
def play_recursive(self):

    if not self.hexagons:
        messagebox.showinfo("oops", "First,Upload the model")
        self.canvas.delete("all")

    directory_new = self.check_prescreenshot()
    self.clear_model_lines_text()
    last_time = self.scene_events[-1].time_stamp
    self.timer = MyThread(last_time=int(last_time), current_time=-1, label=self.clock, root=self.root,
                          speed_mode=self.speed_mode)

    self.set_video(self.timer)  # start the video recorder
    self.timer.start()
```

Figure 3.1: The pseudo-code for starting video recorder for capturing time.

```python
class MyThread(threading.Thread):

    # Thread class with a _stop() method.

    # The thread itself has to check

    # regularly for the stopped() condition.

    def dds__init__(self, last_time=0, current_time=0, label=None, root="", speed_mode=0):
        super(MyThread, self).__init__()
        self.label = label
        self.last_time = last_time
        self.current_time = current_time
        self.root = root
        self.speed_mode = speed_mode
        self._stop_event = threading.Event()

    def start_counter(self):
        if self.stopped():
            return
        self.current_time += 1
        self.label['text'] = f"TIME:{str(self.current_time)}s" if self.current_time > -1 else 0
        self.label.config(font=("Arial Narrow", 13))
        if self.current_time < self.last_time:
            self.label.after(self.speed_mode, self.start_counter)
        else:
            self.stop()

    def stop(self):
        self._stop_event.set()

    def stopped(self):
        return self._stop_event.isSet()

    def run(self):
        self.start_counter()
```
Figure 3.2: The pseudo-code for recording time for an instantiation.

3.2.3. Modeling complex operations

This study attempts to capture variations in hospital-to-home transition processes of frail patients as a demonstration of the incremental improvement of the DynaFRAM compared to other FRAM related tools. In this section, the steps of model generation with the FMV software are described. Then, the method of importing the FRAM model into the DynaFRAM tool is described, along with an example of how a specific patient instantiation is treated in DynaFRAM. The method used to characterize variability is explained with the aid of examples.

3.2.3.1. A model of complex operations constructed by the FMV tool

The FMV software was used to build a functional model of a complex healthcare operation. A functional model involves function identification, function description, and relationship specification. Figure 3.4 shows the FRAM model of a hospital-to-home transition process for frail older people built by (Salehi, Hanson, et al., 2021). The FMV software was employed to model the transition process. The model illustrates functions constituting the transition process for frail older people. The functions shown in the model could be executed while a case (frail patient) is transferred from hospital to home. In fact, the model involves the potential functions that each case (frail patient) might pass through to transit from hospital to home. It includes 38 functions starting from introducing a patient to hospital to readmitting the patient (Figure 3.4).

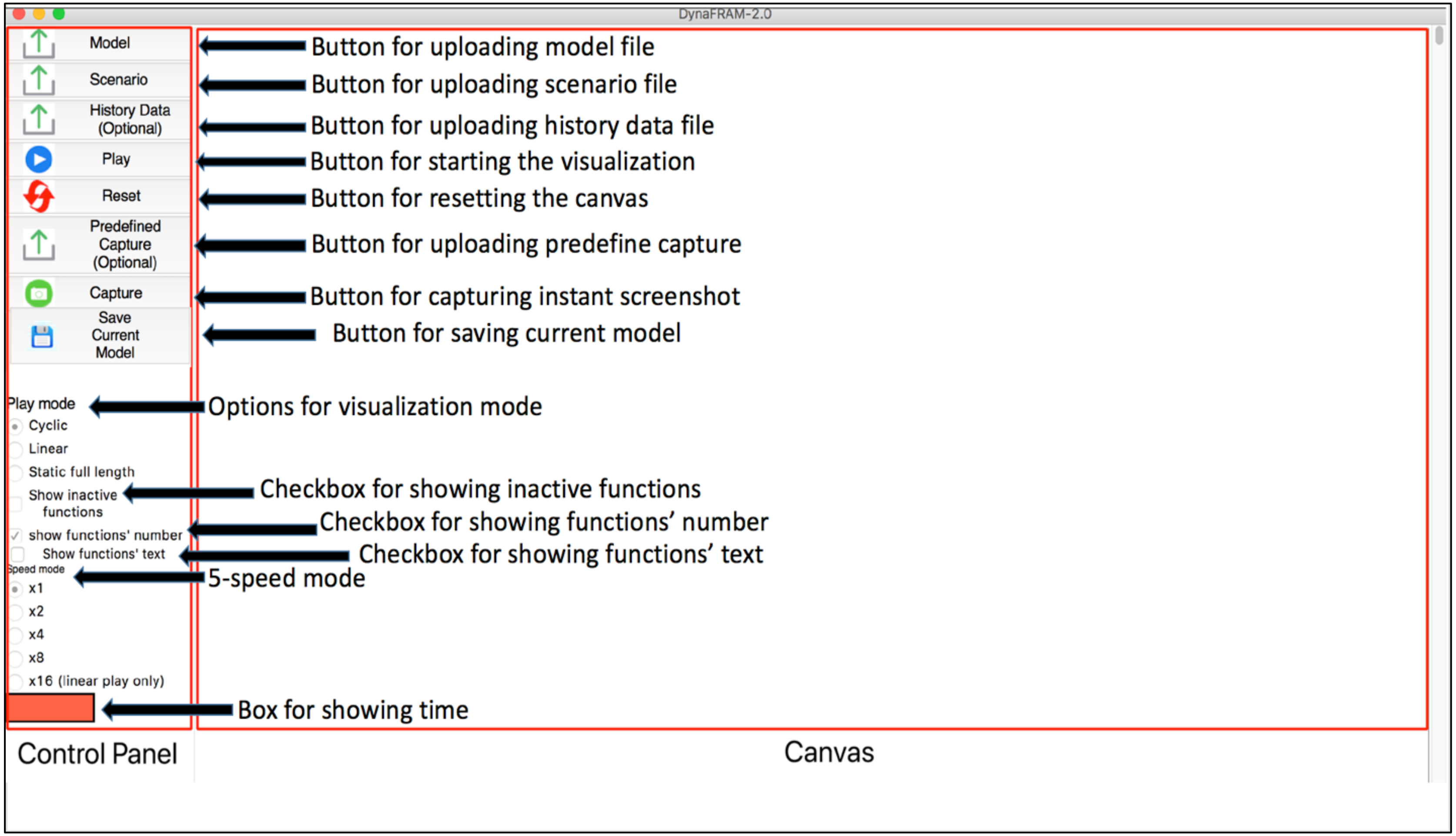

Figure 3.3: A general view of the DynaFRAM tool.

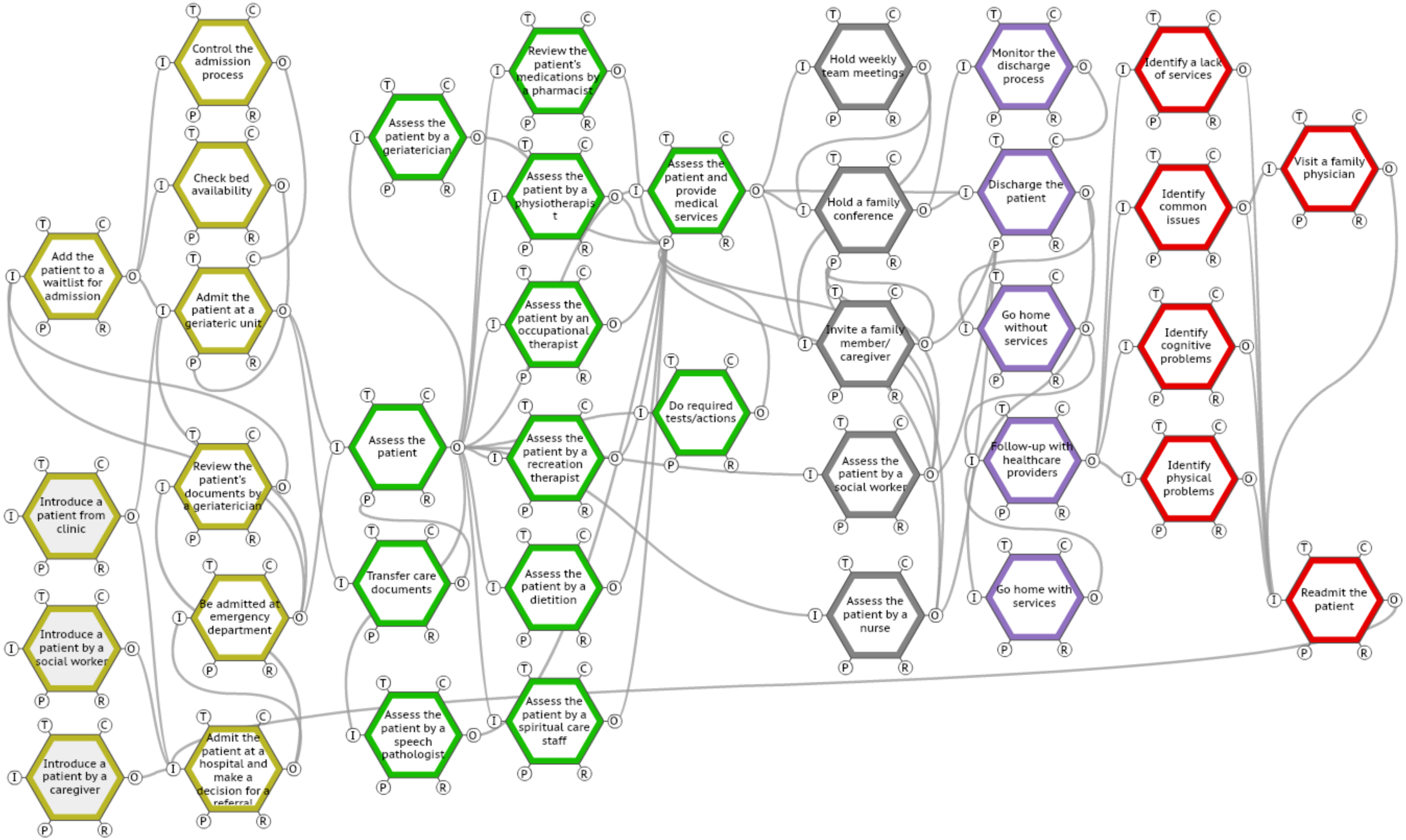

Figure 3.4: The comprehensive FRAM model of the hospital-to-home transition process for frail older patients built by Salehi, Hanson, et al. (2021).

3.2.3.2. Using the DynaFRAM in practice

The applicability of the DynaFRAM for visualizing and capturing variability is evaluated through its use in healthcare operations. The transition process of frail patients from hospital to home is a complex operation, which requires the use of a systemic approach to understand interactions between different elements, including healthcare providers, patients, and caregivers. The capability of the DynaFRAM tool was tested in the transition process of frail patients. Data related to six frail patients during the transition process from three hospitals in Canada were collected (Table 3.2). It is also able to identify functional interdependencies and to capture functional variability.

In the current study, the DynaFRAM was applied to the transition process with the aim of capturing and visualizing different types of variability in order to enhance the transition quality of frail patients. The first step is to upload the FRAM model of the transition process, which was built with the FMV software by (Salehi, Hanson, et al., 2021) (Figure 3.4). The DynaFRAM tool does not produce a model, but employs the models produced with the FMV software. Figure 3.5 shows a FRAM model of the transition process imported into the DynaFRAM tool. As shown in the figure, each function is distinguished with a unique number. The unique numbers are useful replacements for long names of functions, particularly in scenarios. The next step is to upload a scenario related to a patient, which includes the data associated with different functions involved in the transition process of the patient. Table 3.2 identifies 6 transition scenarios, one each for 6 patients. The information for Scenario 3 (patient 1 from city 2) is presented in Table 3.3. “Time” (needed for executing a function), "active function", "active function output", "downstream coupled function", and "coupled function aspect" constitute a scenario in the DynaFRAM, as shown in Table 3.3. It is noteworthy that time unit used for executing functions of all six scenarios is second. The information of other scenarios related to other patients is presented in Appendix A.1. After uploading the model and the relevant scenario, the model can be run. As shown in Figure 3.3, the "Play" button allows running a model in the DynaFRAM tool.

Table 3.2: Categorizing patients in the format of scenarios.

Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
patient 1 of city 1	patient 3 of city 1	patient 1 of city 2	patient 2 of city 2	patient 1 of city 3	patient 2 of city 3

Table 3.3: The information of Scenario 3 provided for patient 1 of city 2.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Fractured left ankle and fracture of left distal tibia	6	I
2	6	Referral to a geriatrician	5	I
3	5	Long background review	7	I
15	7	Almost 12 days	8	I
27	8	Hospitalizing at geriatric unit	22	I
28	22	Left distal tibia/Atrial fibrillation	35	I
29	22	Nurse assessment	2	I
30	2	Satisfactory	35	P
31	22	SW assessment	11	I
32	11	Satisfactory	35	P
33	22	Physiotherapy	1	I
34	1	Wheelchair is required	35	P
35	22	Occupational therapy	21	I
36	21	Satisfactory	35	P
37	22	Recreation therapy	23	I
38	23	Satisfactory	35	P
39	22	Dietitian assessment	24	I
40	24	Satisfactory	35	P
41	35	Wheelchair/blister pack	0	I

42	35	Informing for discharge	26	I
43	26	Spouse/son	0	P
44	0	Acceptable ability for discharge	4	I
45	4	Extra Mural Program with a physiotherapist	14	I
46	4	Wheelchair/blister pack/no discharge planner (case coordinator)	3	I
47	14	Physiotherapist visited the participant in their home	3	I

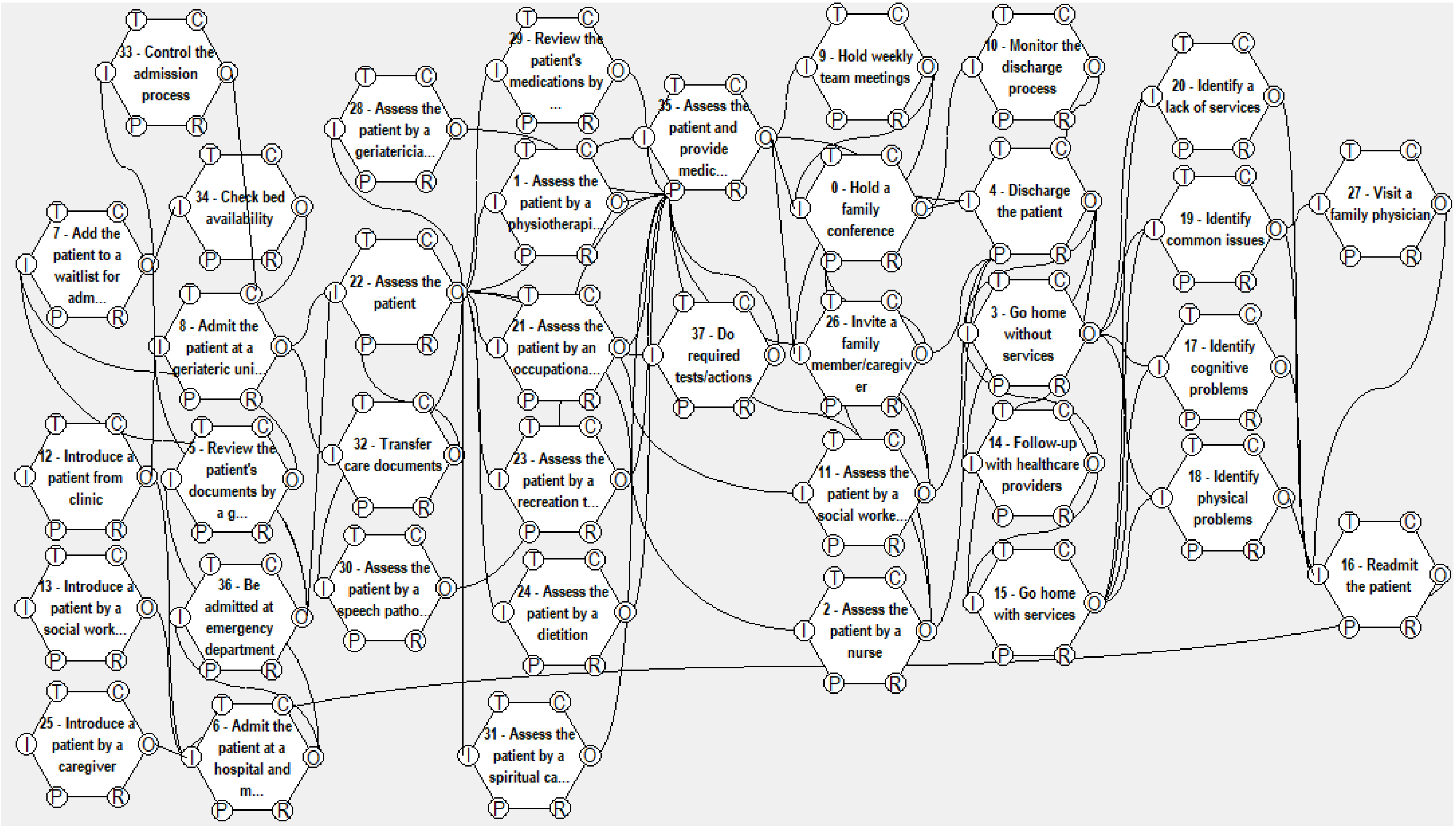

Figure 3.5: The transition model imported in the DynaFRAM tool.

3.3. Results and discussion

Operations can be monitored for understanding the performance of the entire system once the functional model is constructed (Smith et al., 2020). Constructed FRAM models provide a basis for identifying the potential pathways of both successful and unsuccessful operations. Capturing and interpreting performance variability helps understand the ways that outcomes of a system (successes and failures) are attained. This study strives to capture qualitative, quantitative, and temporal characteristics of variability with the DynaFRAM. A healthcare-related case study was chosen to demonstrate the capability of the DynaFRAM in characterizing and capturing variations. The following subsections include the description and discussion of capturing variability with the DynaFRAM.

3.3.1. Capturing qualitative characteristic of variability

The qualitative characteristic of variability can be captured both for functional output(s) and for the outcomes of the entire system with the DynaFRAM. In this subsection, both states are described and discussed.

Capturing functional output variations is of great importance as the variability observed in the output(s) of a function can affect the output(s) of downstream functions. The outcome of the entire system may consequently be affected with the variability of coupled functions. The DynaFRAM provides a possibility to capture and visualize functional output variations. In this section, the variability regarding qualitative functional outputs is discussed. The DynaFRAM helps understand why the nature of functional outputs is variable. The output(s) of a specific function can be variable for different cases. This is characterized through comparing the output(s) of a specific function for different cases. To this end, the transition model (Figure 3.5) should be run for each case/patient based on the scenario provided for that patient. Figures 3.6a-3.6f illustrate the output of <Discharge the patient> function for six patients in the transition process. A comparison of functional outputs visualized in Figures 3.6a-3.6f shows the output of the function is variable for the six patients in the transition process. This example demonstrates the capability of the DynaFRAM in visualizing qualitative functional output variations.

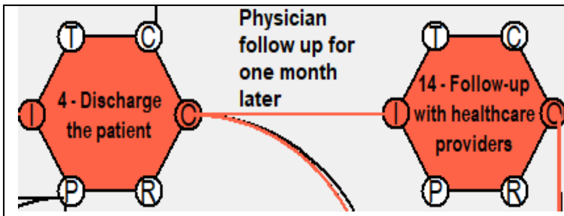

Figure 3.6a: Patient 1 from city 1.

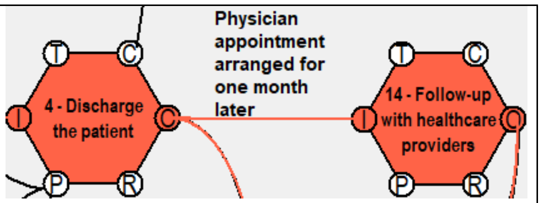

Figure 3.6b: Patient 3 from city 1.

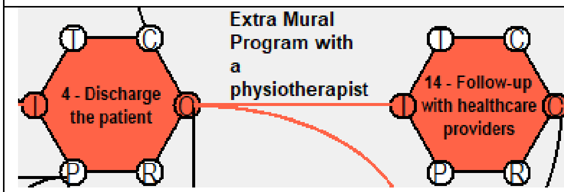

Figure 3.6c: Patient 1 from city 2.

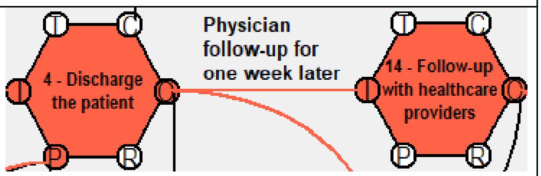

Figure 3.6d: Patient 2 from city 2.

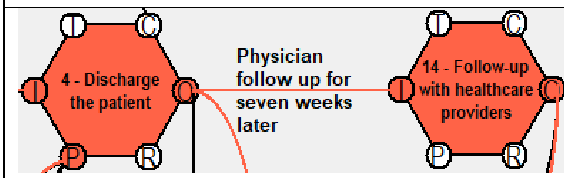

Figure 3.6e: Patient 1 from city 3.

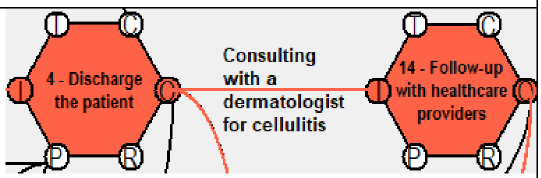

Figure 3.6f: Patient 2 from city 3.

Another advantage of using the DynaFRAM is to record instantiations in order to capture qualitative characteristics of variability between recorded instantiations. In this study, the process of transitioning a frail patient from hospital to home is considered an instantiation. The functions that are executed for each case specify the pathway of that case. The DynaFRAM is able to identify active functions involved in each instantiation. Inactive functions are also identifiable for each case. Two instantiations associated with two patients are presented in Figures 3.7 and 3.8. The number of active functions that patient 1 from city 1 passed through during the transition process is 25 (Figure 3.7), whereas the number is 18 for patient 1 from city 2 (Figure 3.8).

Processes can be mapped, and instantiations can be recorded with the DynaFRAM to capture the variations associated with the outcome(s) of the entire system. A comparison of instantiations characterizes the range of variability in the recorded instantiations. As illustrated in Figures 3.7 and 3.8, the pathway of patient 1 from city 1 is different from the one that patient 1 from city 2 experienced. That is, the two instantiations included different active functions with different functional outputs. The instantiations show that the two patients experienced different paths and their transitions ended up in different functions with different outcomes although both started from a same function. Using the DynaFRAM allows mapping processes and recording instantiations of variability that improves tractability of complex operations. The results showed that the transition process of patient 1 from city 2 resulted in going home and staying there (Figure 3.8), whereas patient 1 from city 1 was readmitted to the hospital (Figure 3.7). Variability regarding functional pathways or instantiations provides required information to analyze the outcomes of an entire system. Analyzing the variability captured in functional pathways can provide insight into complex operations and help healthcare providers and operations managers to manage better processes.

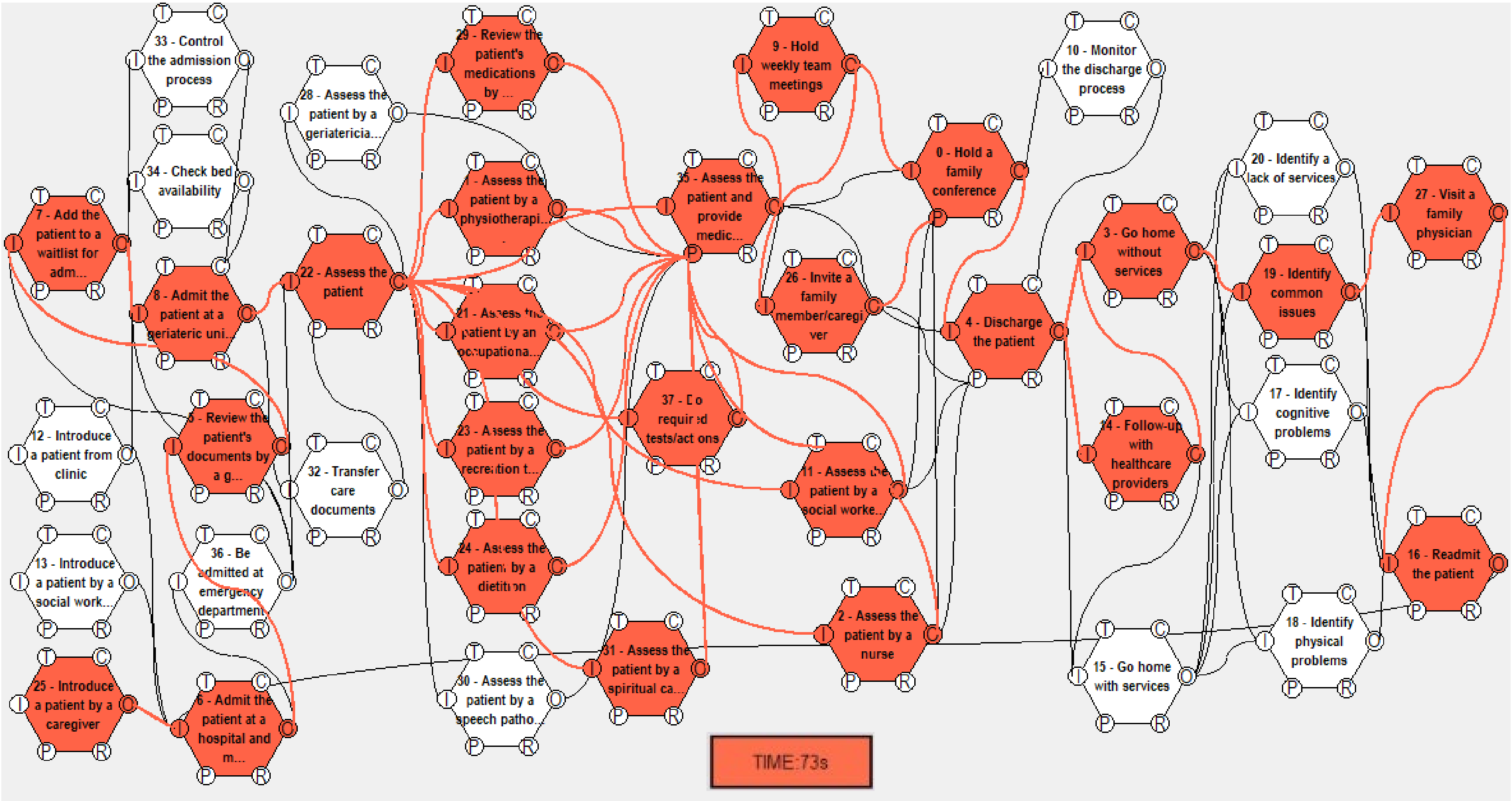

Figure 3.7: Pathway/instantiation for patient 1 from city 1.

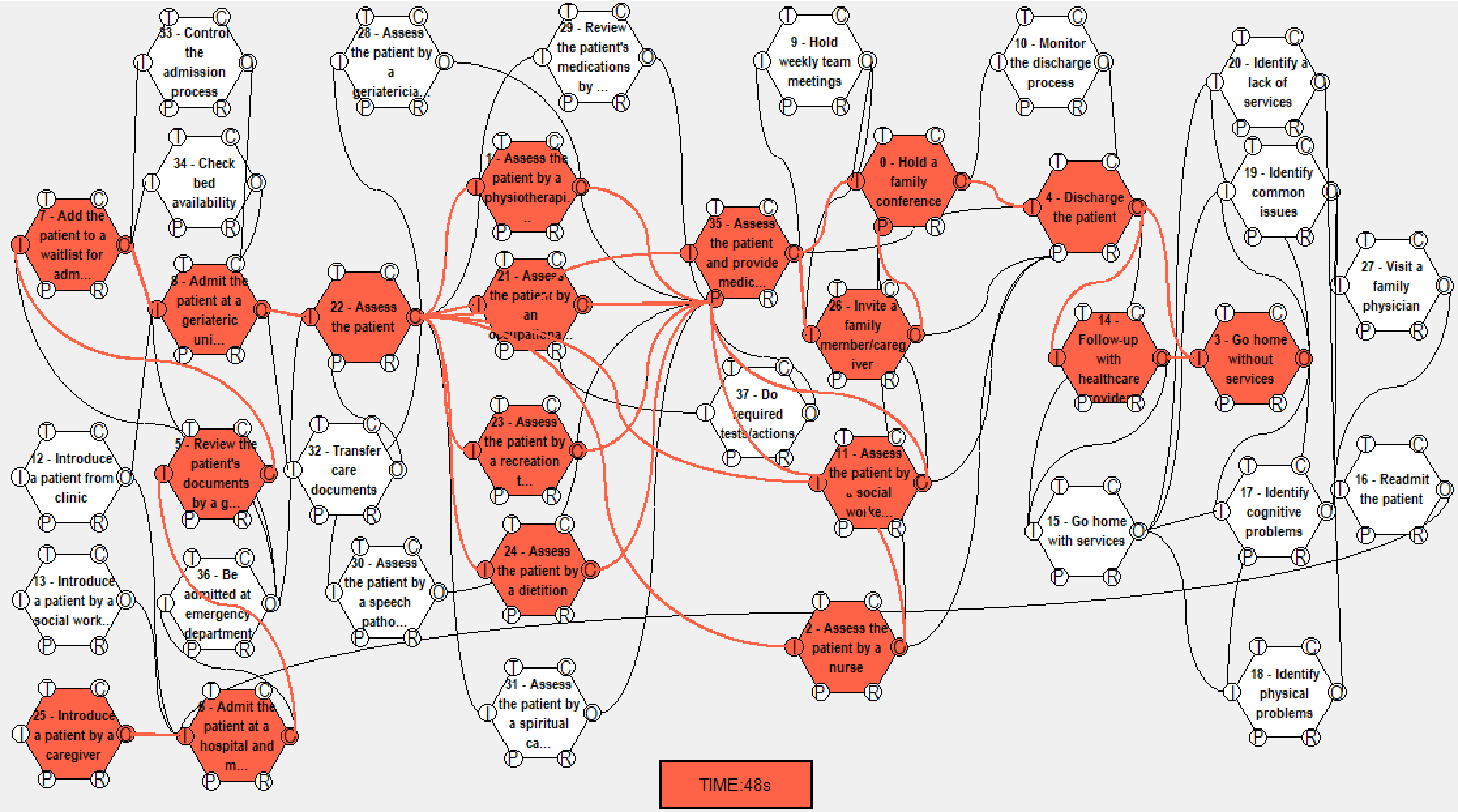

Figure 3.8: Pathway/instantiation for patient 1 from city 2.

3.3.2. Capturing the quantitative characteristic of variability

The output(s) of a function may be quantitative or numerical. The number of medications that a patient should take is an example of a quantitative functional output. Understanding the variability of quantitative functional outputs is as important as qualitative functional outputs. To capture the quantitative characteristic of variability, numerical functional outputs should be specified. In this study, numerical dissimilarities and differences in functional outputs are indicative of quantitative variability. The DynaFRAM is able to characterize dissimilarities in the quantitative dimension of functional outputs. To this end, the transition model was run with DynaFRAM for the six patients in order to characterize the number of caregivers that accompanied each patient during the transition process. The results are shown in Figures 3.9a-3.9f. As illustrated in the figures, the functional output of Function 26 (<invite a family member/caregiver>) is variable as the number of caregivers is different for various patients: two caregivers for three patients (Figures 3.9a, 3.9c, and 3.9f) and one caregiver for three patients (Figures 3.9b, 3.9d, and 3.9e). Capturing quantitative characteristic of variability can help analysts identify the sources of variability that influence the output(s) of downstream functions and even the outcome of the entire system.

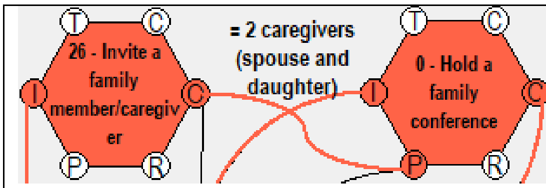

Figure 3.9a: Patient 1 from city 1.

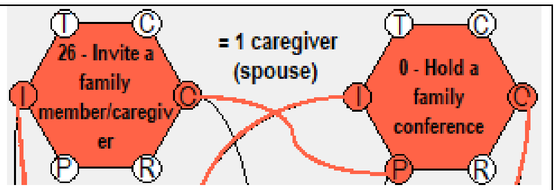

Figure 3.9b: Patient 3 from city 1.

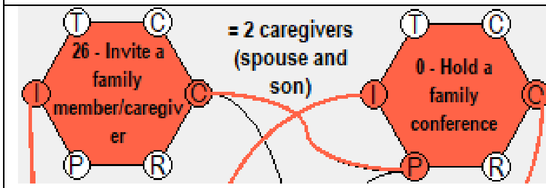

Figure 3.9c: Patient 1 from city 2.

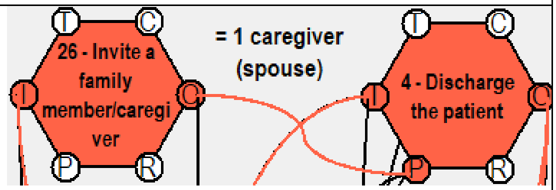

Figure 3.9d: Patient 2 from city 2.

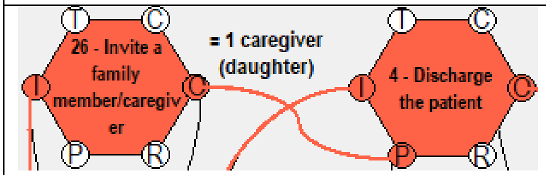

Figure 3.9e: Patient 1 from city 3.

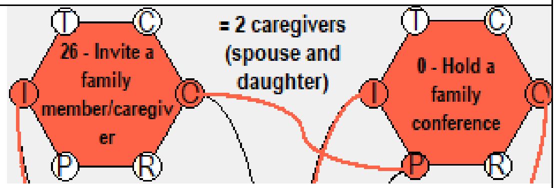

Figure 3.9f: Patient 2 from city 3.

3.3.3. Capturing temporal variability

Variability might occur because of time pressure as time variations can affect the output(s) of functions or the outcome(s) of the entire system (Raben, Viskum, et al., 2018). The DynaFRAM is able to capture temporal variations both for a specific function and for the entire system.

Videos 1-3 in Appendix A.2 show time captured to execute <Add the patient to a waitlist for admission> function (Figure 3.5: Function 7). As shown in the videos, the execution time of the function is variable for the three patients: 12 time units for patient 1 from city 1 (Scenario 1), one time unit for patient 2 from city 2 (Scenario 4), and five time units for patient 2 from city 3 (Scenario 6). This temporal variability may affect downstream functions in the transition process of each patient, and may even influence the outcome of the entire system.

The DynaFRAM permits the execution of a FRAM model for different cases. The outputs of functions may be variable when different cases are executed, and only some functions may be carried out at a specific time. An instantiation of an event can be recorded through tracking the variable processes over time. Two recorded instantiations are presented in the format of video in Appendices A.3 and A.4 for patient 1 from city 1 (Scenario 1) and patient 1 from city 2 (Scenario 3). As shown in Videos 4 and 5 (Appendices A.3 and A.4), time was captured for the instantiations with the DynaFRAM based on the scenarios provided for the two patients. The information of Scenario 1 (patient 1 from city 1) is presented in Appendix A.1 and the information of Scenario 3 (patient 1 from city 2) is shown in Table 3.3. The transition time captured for patient 1 from city 1 was 73 time units (seconds) whereas the transition process lasted 48 time units (seconds) for patient 1 from city 2, as shown in Figures 3.7 and 3.8. The temporal variability observed in the transition processes of the two patients resulted from different time values recorded for executing the active functions of the two instantiations. Understanding temporal variations in the transition processes can help healthcare providers to improve the quality of care for frail patients.

3.4. Study limitations

This study had two limitations that should be mentioned. The ability of the DynaFRAM tool was assessed to capture different characteristics of variability in healthcare operations. First, the information used in this study was limited to just six patients although in-depth data were gathered for each patient. A bigger sample size could be a better and more accurate basis for evaluating the capability of the tool in capturing variability. The second limitation was associated with quantitative functional outputs. The outputs of functions for all six patients were qualitative except the output of Function 26 (<invite a family member/caregiver>). This limitation was a barrier in showing the ability of the DynaFRAM in capturing quantitative characteristics of variability.

3.5. Conclusions

The DynaFRAM, a dynamic version of the FRAM, was developed and applied to healthcare operations to investigate performance variability in complex operations. It is suitable for studying and analyzing complex operations characterized by functions. In this study, the DynaFRAM was applied successfully to a transition model of frail patients to capture and visualize different characteristics of variations. The results showed the incremental improvements of the DynaFRAM compared to other FRAM related tools. According to the results of this study, the DynaFRAM was able to capture the qualitative characteristics of variability regarding functional outputs and the outcomes of the entire system. Another benefit of using the DynaFRAM was to capture quantitative characteristic of variability in complex operations. Another benefit of the DynaFRAM was demonstrated through capturing temporal variations both in functional outputs and in the outcomes of the entire system. The application of the DynaFRAM to complex operations enables gaining operational insight that can improve experts’ understanding of the operations they manage.

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References

Adriaensen, A., Patriarca, R., Smoker, A., & Bergström, J. (2019). A socio-technical analysis of functional properties in a joint cognitive system: a case study in an aircraft cockpit. *Ergonomics*, *62(12),* 1598-1616.

Aguilera, M. V. C., da Fonseca, B. B., Ferris, T. K., Vidal, M. C. R., & de Carvalho, P. V. R. (2016). Modelling performance variabilities in oil spill response to improve system resilience. *Journal of Loss Prevention in the Process Industries*, *41*, 18–30.

Anvarifar, F., Voorendt, M. Z., Zevenbergen, C., & Thissen, W. (2017). An application of the Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood defences in the Netherlands. *Reliability Engineering & System Safety*, *158*, 130–141.

de Vries, L. (2017). Work as done? Understanding the practice of sociotechnical work in the maritime domain. *Journal of Cognitive Engineering and Decision Making*, *11*(3), 270–295.

Hill, R., & Hollnagel, E. (2016). *Instructions for use of the FRAM Model Visuliser (FMV)*. In *Advances in Human Aspects of Transportation* (pp. 399–411). Springer.

Hollnagel, E. (2012). *FRAM, the functional resonance analysis method: modelling complex socio-technical systems*. Ashgate Publishing, Ltd.

Hollnagel - https://functionalresonance.com/the-fram-model-interpreter.html (accessed 2021-08-13).

Lee, J., & Chung, H. (2018). A new methodology for accident analysis with human and system interaction based on FRAM: Case studies in maritime domain. *Safety Science*, *109*, 57–66.

Li, W., He, M., Sun, Y., & Cao, Q. (2019). A proactive operational risk identification and analysis framework based on the integration of ACAT and FRAM. *Reliability Engineering & System Safety*, *186*, 101–109.

Patriarca, R., & Bergström, J. (2017). Modelling complexity in everyday operations: functional resonance in maritime mooring at quay. *Cognition, Technology & Work*, *19*(4), 711–729.

Patriarca, R., Di Gravio, G., & Costantino, F. (2017). A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. *Safety Science*, *91*, 49–60.

Patriarca, R., Di Gravio, G. and Costantino, F., 2017, December. myFRAM: An open tool support for the functional resonance analysis method. In 2017 2nd International Conference on System Reliability and Safety (ICSRS) (pp. 439-443). IEEE.

Patriarca, R., Di Gravio, G., Woltjer, R., Costantino, F., Praetorius, G., Ferreira, P. & Hollnagel, E., 2020. Framing the FRAM: A literature review on the functional resonance analysis method. *Safety Science*, *129*, p.104827.

Praetorius, G., Graziano, A., Schröder-Hinrichs, J.-U., & Baldauf, M. (2017). Fram in FSA—Introducing a function-based approach to the formal safety assessment framework.

Raben, D. C., Viskum, B., Mikkelsen, K. L., Hounsgaard, J., Bogh, S. B., & Hollnagel, E. (2018). Application of a non-linear model to understand healthcare processes: using the functional resonance analysis method on a case study of the early detection of sepsis. *Reliability Engineering & System Safety*, *177*, 1–11.

Ransolin, N., Saurin, T. A., & Formoso, C. T. (2020). Integrated modelling of built environment and functional requirements: Implications for resilience. *Applied Ergonomics*, *88*, 103154.

Salehi, V., Hanson, N., Smith, D., McCloskey, R., Jarrett, P. & Veitch, B., 2021. Modeling and analyzing hospital to home transition processes of frail older adults using the functional resonance analysis method (FRAM). *Applied Ergonomics*, *93*, p.103392.

Salehi, V., Veitch, B., & Smith, D. (2021). Modeling complex socio-technical systems using the FRAM: A literature review. *Human Factors and Ergonomics In Manufacturing, 31*(1), 118-142.

Shirali, G.A. & Ebrahipour, V., 2013. Proactive risk assessment to identify emergent risks using functional resonance analysis method (FRAM): A case study in an oil process unit. *Iran Occupational Health, 10(6),* 33-46.

Smith, D., Veitch, B., Khan, F., & Taylor, R. (2020). Integration of Resilience and FRAM for Safety Management. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *6*(2), 4020008.

Studic, M., Majumdar, A., Schuster, W., & Ochieng, W. Y. (2017). A systemic modelling of ground handling services using the functional resonance analysis method. *Transportation Research Part C: Emerging Technologies*, *74*, 245–260.

Tian, J., Wu, J., Yang, Q., & Zhao, T. (2016). FRAMA: a safety assessment approach based on Functional Resonance Analysis Method. *Safety Science*, *85*, 41–52.

Woltjer, R. & Hollnagel, E., 2008. Functional modeling for risk assessment of automation in a changing air traffic management environment. *In Proceedings of the 4th international conference working on safety (Vol. 30)*.

Chapter 4

Modeling and analyzing hospital to home transition processes of frail older adults using the functional resonance analysis method (FRAM)*

Co-authorship statement. A version of this chapter has appeared in the journal *Applied Ergonomics* published *by Elsevier*. The lead author, Vahid Salehi, has generated the model and extracted the patient-related data for running the model. Co-authors from University of New Brunswick gathered research data for modelling and verified the generated model. The co-author Dr. Natasha Hanson led the data collection process. The co-author Dr. Doug Smith contributed to shaping the interview questions to get the data we used to build the model. Co-authors Prof. Brian Veitch and Dr. Smith supervised the study. All authors read and approved the final draft.

Abstract. The main purpose of this study was to model and analyze hospital to home transition processes of frail older adults in order to identify the challenges within this process. A multi-phase, multi-sited and mixed methods design was utilized, in which, Phase 1 included collecting semi-structured interviews and focus group data, and Phase 2 consisted of six patient/caregiver dyad prospective case studies. This study was conducted in three hospitals in three cities in a single province in Canada. The

* Salehi, V., Hanson, N., Smith, D., McCloskey, R., Jarrett, P., & Veitch, B. (2021). Modeling and analyzing hospital to home transition processes of frail older adults using the functional resonance analysis method (FRAM). *Applied Ergonomics*, *93*, 103392. https://doi.org/10.1016/j.apergo.2021.103392

Functional Resonance Analysis Method (FRAM) was employed to model daily operations of the transition process. The perspectives of both healthcare providers and patients/caregivers were used to build the FRAM model. The transition model was then tested using a customized version of the FRAM. The six patient/caregiver cases were used in the process of testing the FRAM model. The results of building the FRAM model showed that five categories of functions contributed to the transition model, including admission, assessment, synthesis, decision-making, and readmission. The outcomes of using the customized version of the FRAM revealed challenges affecting the transition process including waitlists for geriatric units, team-based care, lack of a discharge planner, financial concerns, and follow-up plans. The findings of this study could assist managers and other decision makers to improve the transition processes of frail older adults by addressing these challenges. The FRAM method employed in this study can be applied widely to identify work practices that are more or less successful, so that procedures and practices can be adapted to nudge healthcare processes towards paths that will yield better outcomes.

Keywords: Transition process; Frail patients; Functional Resonance Analysis Method (FRAM); Geriatric unit; Healthcare providers.

4.1. Introduction

The healthcare sector is under tremendous pressure from the competing requirements of increasing efficiency, safety, and economic viability (Hollnagel & Braithwaite, 2019). One of the most significant challenges in healthcare systems is the maintenance of health in old age. The proportion of people aged 65 and older is projected to increase worldwide in the coming decades (World Health Organization, 2015). During the last three decades, the population of people in the age range of 65 years and above has witnessed an increasing trend in Canada (Canadian Frailty Network, 2020). Moreover, life expectancy has increased in developed countries, which has been one of the greatest achievements of public health in the twentieth century (Oeppen & Vaupel, 2004).

As people age, there is a decline in their physical and mental capacity, and the risk of morbidity and frailty increases. Frailty is a reduction in the capability to respond to stressors and an increased vulnerability to adverse outcomes (Fried et al., 2001). It has important implications for the capability to retain independent, high quality living, and carries an increased risk of hospital visits, disability, and death (Heuberger, 2011). Aging intensifies the degree of frailty, making it more likely that illness in seniors will contribute to some degree of functional decline (Ebrahimi et al., 2013; Williams et al., 2009). The vulnerability of frail older adults to unexpected events and their functional decline while being hospitalized heightens the need for developing an inclusive approach to address the issues and needs of frail older adults.

Healthcare, a socio-technical system, exhibits dynamic interactions between technology, humans, organizations, and the environment (Holden et al., 2013). Hospital-to-home transition processes are complex given that multiple human-organizational factors are involved (O'Hara et al., 2020; Robinson et al., 2012). The perceptions of different stakeholders, such as frail patients, caregivers, and healthcare providers, make such transitions more complicated. To address the complexity of such a process, systemic approaches are required as they are able to capture the interdependencies among different elements (Hollnagel, 2012b; Laugaland et al., 2014). The fundamental intention of human factors, especially systemic approaches is to improve the safety of people in complex processes, such as care transitions (Aase & Waring, 2020). To cope with the complexity of transitional processes and to promote successful transitions, the involvement of a variety of health professionals is often required (Nuernberger et al., 2018). Systemic approaches are appropriate for such purposes as they can consider the non-linear and dynamic relationships between different elements (Hollnagel, 2017).

A review of the literature in the fields of human factors/ergonomics and health services research shows that a considerable amount of research has been conducted investigating the transition/discharge process of frail patients from hospital to home (Aase & Waring, 2020; Barnhart & Carpenter, 2016; Randriambelonoro et al., 2020). Some of the studies regarding the transition process of frail patients are reviewed here. Laugaland et al. (2012) conducted a qualitative study for identifying interventions for enhancing patient safety during transitional care of frail patients. The outcomes of the study indicated a number of intervention types, such as organizational interventions, profession oriented interventions, and patient/next of kin oriented interventions. Kianfar et al. (2019) presented a framework of care coordination for chronically ill patients using a comparative method. Interviewing 12 healthcare professionals led to identifying factors influencing care coordination. “Exchanging information about patient transition”, “arranging services and equipment for the patient”, “helping the patient with appointments and transportation”, and “scheduling follow-up to review patient status” were some of the factors that influenced the patient transition. Williams et al. (2009) investigated emergency department-to-home transitions of older adults using the Systems Engineering Initiative for Patient Safety (SEIPS) 2.0 model. The SEIPS model was applied for analyzing processes that occur across multiple work systems. The results showed the SEIPS model is able to identify and model work system barriers. It is also capable of providing a basis for evaluating the patient transition across system boundaries. Aase & Waring (2020) conducted a qualitative study to establish a framework to investigate safety and quality in care transitions. The results of the study showed that some components, such as communicative, cultural, collaborative, patient-based, and competency-based factors affect the safety and quality of the care transitions. A synthesis of the non-FRAM related studies indicated that there is a lack of a detailed model of the transition process of frail patients (Rennke et al., 2013). Additionally, the models presented in the studies suffer from investigating non-linear relationships between different elements of the transition process. The inherent variability in everyday activities that can potentially lead to undesired outcomes was also denied in the studies (Laugaland et al., 2014).

The functional resonance analysis method (FRAM), a systemic approach, is used to model everyday activities to demonstrate the complexity of a system (Hollnagel, 2012b; Salehi, Veitch, et al., 2021). The FRAM is a function-based approach that is used to describe work as done, show interactions between functions, and identify performance variability (Bjerga et al., 2016; Hollnagel, 2012b). It has been successfully employed for assessing risks and investigating events/accidents in complex systems, such as healthcare (Buikstra et al., 2020; Hollnagel, 2012b). Table 4.1 shows a list of the studies, which have used FRAM in this capacity in order to address issues related to healthcare systems.

A review of the literature shows some studies explored the transition process of frail patients using the FRAM. Laugaland et al. (2014) used FRAM to identify functions, variability, and performance shaping factors in the discharge process of 20 frail older hospitalized patients. The study outcomes indicated that the FRAM is capable of providing a detailed understanding of the discharge process, and of recognizing the sources of performance variability influenced by various factors. Recently, Buikstra et al. (2020) employed the FRAM for analyzing the discharge process of frail patients and for understanding variability in everyday operations of the discharge process. The results of the study highlighted the role of the FRAM in modeling complex processes and addressing issues associated with performance adjustments in everyday activities of frail older adults. The results of the FRAM also showed that changes based on the aggregation of variability could decrease the probability of undesired outcomes for frail older patients. O'Hara et al. (2020) also applied the FRAM to model transitional care using different stakeholder perspectives. The FRAM model was used to expand a theory of change for guiding intervention development. The study identified 27 functions with related interdependencies. The results of the study showed that concentrating on activities such as maintaining patient mobility and reinforcing the understanding of medication and conditions help to enhance outcomes for frail patients after discharge.

A synthesis of the FRAM related studies revealed that no studies to date have fully modelled, investigated, and monitored issues related to both pre-discharge and post-discharge processes (follow-up and readmission) for frail patients using FRAM (Table 4.1). To this end, the current study selected the FRAM to represent a functional model of the complexity of interactions between different elements/functions of the hospital-to-home transition process. This study also aimed to monitor the transition process of frail patients and to identify challenges they face during the transition process. The current study is different from O'Hara et al. (2020) in both data collection approaches and aims, although there are some similarities. As Table 4.1 shows, the current study used textual review, home observations, and questionnaires to collect data, in addition to other approaches used by O'Hara et al. (2020). Another dissimilarity is that the current study incorporated the perspectives of both healthcare providers and patients/caregivers in the model of the transition process. Another unique characteristic of this study was the use of a customized version of the FRAM to monitor patients' transition processes between admission and (possible) readmission processes. It helps identify challenges affecting the transition process, which is a unique aim of this study. In summary, this research sought to identify some key problems faced by frail older people transitioning from hospital to home in the community by developing a FRAM-based model. In this regard, we aim to: (1) Develop a comprehensive model of the hospital-to-home transition process for frail patients; (2) Monitor the transition process of frail patients with a customized version of the FRAM; and (3) Identify challenges in the transition process based on variations observed in the functional outputs of the transitions. The comprehensive model will be discussed further in Subsection 4.4.1. (Constructing the FRAM model).

Table 4.1: The characteristics of this study versus other relevant studies in the healthcare sector.

Study	Data collection approach						Method		Feature			Objective		
	Observation	Interview	Focus group	Textual review	Home observations	Questionnaire	FRAM	DynaFRAM	Frailty	Pre-discharge	Post-discharge	Comprehensive model	Patient monitoring	Challenges
This study	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
(O'Hara et al., 2020)	✓	✓	✓				✓		✓	✓	✓	✓		
(Buikstra et al., 2020)		✓	✓	✓			✓		✓	✓		✓		
(Damen et al., 2019)		✓					✓							
(Schutijser et al., 2019)	✓	✓					✓							
(Kaya et al., 2019)	✓	✓					✓							
(Rosso & Saurin, 2018)	✓	✓		✓			✓							
(McNab et al., 2018)		✓					✓							
(Raben, Viskum, et al., 2018)	✓	✓	✓	✓			✓							
(Ross et al., 2018)	✓	✓				✓	✓							
(Pickup et al., 2017)	✓	✓		✓			✓							
(Saurin & Werle, 2017)	✓	✓		✓		✓	✓							
(Clay-Williams et al., 2015)			✓				✓							
(Laugaland et al., 2014)	✓	✓					✓		✓	✓				
(Pereira, 2013)			✓				✓							

This paper is organized into seven sections. The first section presented the introduction, comprising a review of studies related to issues faced by frail older adults transitioning from hospital to home and the FRAM as an approach for addressing such issues. The aims of this study and a comparison with some relevant studies were also presented in the first section. The methodology, including research design and the FRAM, is presented in Section 4.2. Section 4.3 is associated with the data collection process. The results of the FRAM, encompassing building and testing a comprehensive transition model, are described in Section 4.4. The results are discussed in Section 4.5. Finally, the limitations of this study and the conclusions are presented in Sections 4.6 and 4.7, respectively.

4.2. Method

4.2.1. Research design

To achieve the goals presented in Table 4.1, this study was conducted in three different hospitals in three different cities in a Canadian province and incorporates the perspectives of healthcare providers, patients, and caregivers. The study employed the FRAM to construct a comprehensive model of the hospital-to-home transition process for frail older adults and provide examples of evidence for identifying challenges faced in the transition process. In this study, frail older adults are those with a Clinical Frailty Score of 6 or higher (Rockwood et al., 2005), upon admission to a geriatric unit. Figure 4.1 encompasses a schematic structure to describe various steps of the current research.

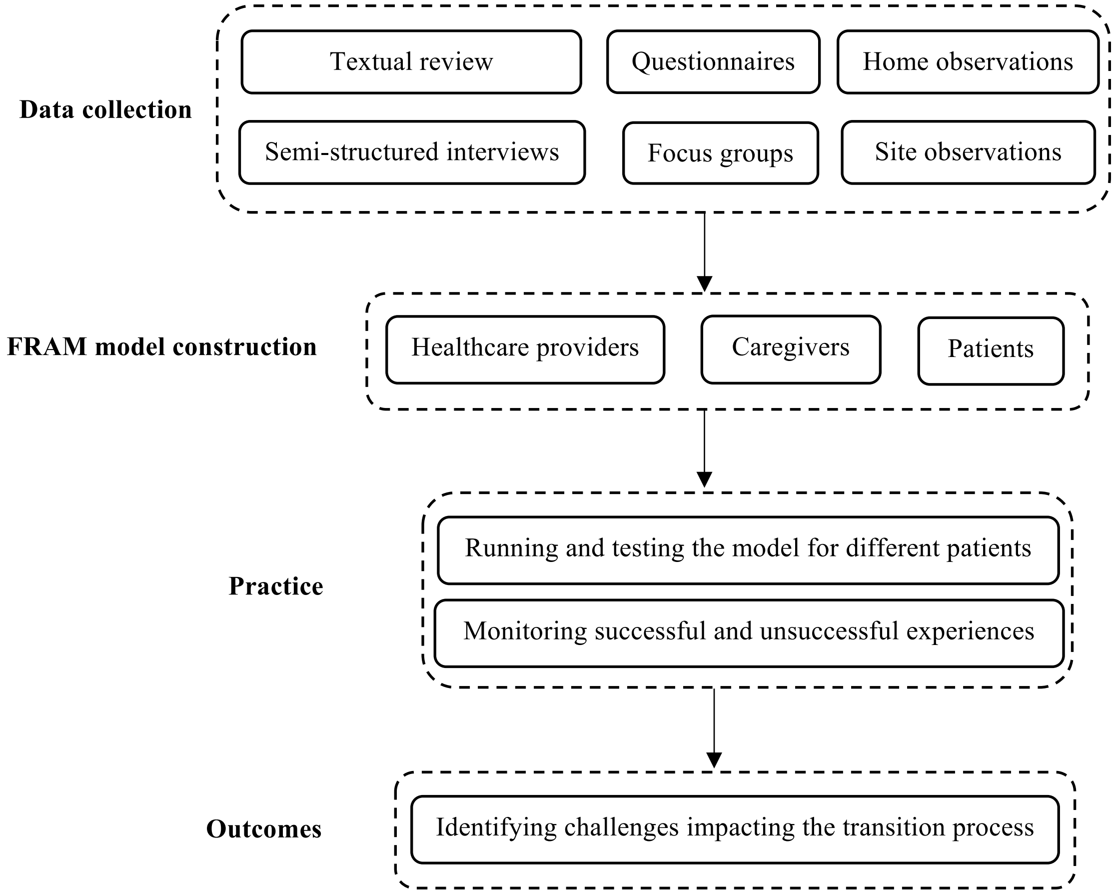

Figure 4.1: The schematic structure of this study.

4.2.2. Functional resonance analysis method (FRAM)

The FRAM is a qualitative approach that is used to visualize and model complex systems (Salehi et al., 2021). The method helps analyze complex socio-technical systems and uncover the complexity in everyday activities (Praetorius et al., 2015). It also provides insights into the functionality of a process, which can improve the background knowledge for any qualitative or quantitative risk assessment. These insights are also used to introduce measures and strategies for enhancing a system's capability to achieve a higher level of safety and resilience (Macchi et al., 2009; Patriarca et al., 2018). As mentioned earlier, the FRAM is a function-based approach.

Functions explain everyday work of a system (Salehi et al., 2021). Technological, human, and organizational functions related to everyday operations constitute the basis of a FRAM model (Ross et al., 2018). A key aim of the FRAM is to identify a system's dynamics through investigating the interdependencies between functions (Patriarca et al., 2017). The FRAM entails four main steps that are described in the following subsections.

4.2.2.1. Identifying and explaining functions

The first step includes identifying and describing functions. These functions can be classified as background or foreground functions. Background functions require a single input or one output and constitute the boundary of a system. Foreground functions are used for the main analysis and require more than one active aspect (Patriarca et al., 2018). Each function is described by up to six aspects, as follows:

- **Inputs:** What a function uses to produce the output
- **Preconditions:** What should be satisfied for a function to perform
- **Resources:** What is consumed to execute a function/activity
- **Time:** Temporal requirements of a function
- **Control:** What supervises or regulates a function
- **Outputs:** The result(s) of a function

4.2.2.2. Identifying performance variability

A FRAM model can be used to understand how the variability and adjustments of a function can affect other functions and thereby the activity as a whole (Hollnagel, 2017). The potential and actual variability of each function's output should be determined in the second step (Tian et al., 2016). One simple way of describing the variability of the output of a function is based on time and precision (Hollnagel, 2017).

4.2.2.3. Functional resonance

The third step focuses on determining the possibility of functional resonance based on dependencies/couplings among functions and their potential/actual variability (Bridges et al., 2018). This step is also known as the aggregation of variability (Patriarca, Di Gravio, & Costantino, 2017a). To take into account the aggregation of variability, specification of upstream-downstream couplings is essential. The variability of an output of a downstream function can be due to the variability of the output from upstream functions that provides the input, requirement, resource, control, or time for downstream functions (Hollnagel, 2017). An example of an upstream-downstream coupling could be the dependency between functions <hold a family conference> and <discharge a patient> (Figure 4.2). According to Figure 4.2, <hold a family conference> as the upstream function provides the input for <discharge a patient> as the downstream function. This type of coupling is the basis of functional resonance.

4.2.2.4. Managing variability

Managing and monitoring variability recognized by the aggregation of variability accounts for the final step. Acceptable (positive) and unacceptable (negative) outcomes emerge from performance variability (Hollnagel, 2017). Managing variability is possible by implementing changes that either dampen the negative effects (absorb variability) or reinforce positive effects (amplify variability) (Patriarca & Bergström, 2017).

In this study, a comprehensive FRAM model of the transition process was built by means of FRAM Model Visualiser (FMV) software developed by Hill & Hollnagel (2016).

4.2.3. A customized version of the FRAM

In this study, a customized version of the FRAM was developed through programming in Python programming language (Figure 4.3). It uses the process monitoring and the performance measurement (PMPM) method introduced by Smith et al. (2020). The customized version employs the models generated by the FRAM to map complex activities/operations, functional signatures to monitor what happens, and system performance measurement to compare outcomes of functional processes. Functional signatures are the basis of monitoring active functions in any given case. Performance measurement helps understand variations in system performance (Doug Smith et al., 2020). The customized version of the FRAM has been developed to visualize what is produced at the end of a function, when it happens, and for how long it happens. The original version of the FRAM (FMV software), in the current form, is unable to visualize variations that occur in the outputs of functions. It does not model variability in a specific and tractable way. The original FRAM speaks of variability in general terms as, "this function has high or low variability" and hypothetically compares if multiple functions are likely to affect the overall system performance by some combination of the variability of those functions. The customized version gives more flexibility to users for generating scenarios and visualizing variations in the outputs of functions in terms of both time and precision. It tracks specific time and quantities of functional outputs as operations are carried out. If we collect many examples, we will have the records of the actual variability that occurs in the operation and not just hypothetical variability. It would be better to base a management decision on a phenomenon that are observable repeatedly in an operation rather than a hypothetical case, which may not or cannot occur. It is noteworthy that the customized version does not generate a FRAM model, but uses the models generated by the FMV software. In the current study, the customized version was used to test the model constructed by the FMV software via running different scenarios for different patients.

4.2.4. Modelling and analysis

To construct and run the FRAM model of the transition process from the multiple sources of data, we used a process of analyzing the qualitative data sets, interpretation, and discussion. The authors operated as a team and would like to present the work as a whole. First, the data were analyzed to draw out the timeline of events and types of activity that characterize the movement of a frail patient from hospital admission to discharge and post-discharge period. Second, the authors met to interpret the data and to discuss how the work processes can be presented into activities and functions. Modeling the transition process was supported by the FMV software. Then, it was discussed by all authors to increase the comprehensibility and reliability of the model.

4.3. Data collection

This was a prospective multi-phased mixed methods design. The data were collected in two phases. Phase 1[13] was comprised of qualitative data collection through semi-structured interviews and focus groups. The data of Phase 1 was the basis for constructing the FRAM model, as well as the site observations from Phase 2[14]. The second phase consisted of patient case studies, which included semi-structured interviews, questionnaires comprising standardized measures (Appendix B.4), observations of health care team meetings and family meetings, textual data sources, including electronic medical record (EMR) documents, and home observations. The data gathered from Phase 2 were used for running the model and monitoring the six patients' transition processes. Table 4.2 shows the distribution of participants in the data collection process. Healthcare providers, including geriatricians, pharmacists, nurses, therapists (physiotherapy, occupational, recreation, and speech language pathologists), spiritual care providers, dietitians, social workers, as well as family caregivers, and patients constituted the participants of this study. Data were collected from healthcare providers, as well as patient and family caregiver perspectives in order to model the process comprehensively. No participants were paid for partaking

[13] The file number of the ethics application related to Phase 1 is 051-2018.
[14] The file number of the ethics application related to Phase 2 is 020-2019.

in the research study. Healthcare providers were working at three hospitals in three different cities, on specialized geriatric units (herein referred to as the research sites). The approximate number of inpatient beds was between 100 and 400 for the three hospitals in the three cities. As indicated in Table 4.2, the information from 10 interviews, three focus groups, and observations made at three sites provided the basis for constructing the FRAM model. Weeks of observations were performed, enabling detailed functions/information to be identified, which were subsequently incorporated in the FRAM model. The information of the six patient cases obtained during the second phase was used for testing the model. Informed consent was obtained from all participants prior to data collection in both phases.

Table 4.2: Participants' distribution for building and testing the FRAM model.

	Participants for building FRAM model					Case studies for testing FRAM model (practice)	
	Phase 1					Phase 2	
	Clinician interviews	Caregiver	Patient	Patient and Caregiver	Focus group	Site observation	Patient and Caregiver Cases
City 1	-	2	1	-	10	7 weeks	2
City 2	1	-	-	1	7	11 weeks	2
City 3	1	1	-	3	9	8 weeks	2
Total	2	3	1	4	-	-	6

4.3.1. Semi-structured interviews

All Phase 1 interviews were subject to convenience sampling and semi-structured in design. Although the interviews had a clear structure, there was room for supplementary questions. A recording device was used, with participant permission, to record all interviews, which were then transcribed verbatim by a member of the research team. Patients and caregivers at all three research sites were asked by healthcare providers, within their circle of care, for permission to be contacted by the research team, if the patient was considered frail (patient with Clinical Frailty Score of 6 or higher) and had been scheduled for discharge or discharged within two months. A member of the research team (all of whom were trained in data collection methods and had previous research experience) then contacted patients and/or caregivers to confirm their interest in participation, set up the interview at a time and place convenient to the participant (which included at their homes and over the telephone). Informed consent was obtained prior to the start of the interview. Eight interviews with patients and caregivers were conducted and the average length of interview was 23 minutes. Iterative thematic analysis was conducted according to the phases of thematic analysis described by (Braun & Clarke, 2006) which are: familiarization with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and then producing the report. This analysis was led by the team's qualitative methodologist (NH), with two other trained research team members. All team members conducted each phase of the analysis with consensus being reached regarding generation of initial codes, searching for themes, reviewing themes, and defining and naming themes. Interviews were analyzed iteratively, as they were transcribed after collection, as such it was clear when saturation was reached, in that no new themes were generated by the addition of further data (Saldaña, 2015), for patient and caregiver interviews. Saturation was also agreed upon by all three research team members conducting the thematic analysis. Healthcare providers who worked within the three data collection sites were invited, via an email from the research team, to participate in focus groups or individual interviews, dependent on their preference. Two healthcare providers chose to participate in individual semi-structured interviews by responding to the email. The team's qualitative methodologist conducted these interviews at a time and place convenient to the healthcare providers (which resulted in data collection at private conference rooms in their workplaces). These interviews averaged 43 minutes.

Participants' perspectives presented in the interviews were used to map the transition process of frail patients. The interviews included the opinions of healthcare providers, patients, and caregivers about what constituted a successful transition from hospital to home, including pre-discharge and post-discharge processes. In addition, participants were asked to detail challenges and factors that influence the transition process (see interview guides in Appendices B.1 and B.2 for each participant group). The interviews yielded information that identified core functions, specified aspects, and recognized performance variability related to each function. Additionally, interviews were conducted with a different group of patients and caregivers in the second phase of data collection to capture patients' experiences and health conditions pre- and post-discharge, including at one week, one month, and three months (Appendices B.5 and B.6).

4.3.2. Focus groups

During Phase 1 data collection three focus groups were carried out at the three research sites. Participants consisted of a convenience sample of healthcare providers who treat patients within the research sites. Healthcare providers who worked within the three data collection sites were invited, via an email from the research team, to participate in focus groups or individual interviews, dependent on their preference. The focus groups were scheduled at a time convenient to those who wished to participate and conducted at a private conference room at the research site. The team qualitative methodologist conducted the focus groups, and the average length was 49 minutes. An audio recorder was used with permission to record all focus groups, and the recordings were subsequently transcribed verbatim by a member of the research team. The healthcare providers were asked to explain the characteristics of a successful transition process, factors influencing the transition process, and their respective roles within this process (Appendix B.2). Table 4.2 shows the number of participants in the three focus groups. Iterative thematic analysis (Braun & Clarke, 2006), following the same process detailed above and with the same research team members as the above semi-structured interviews, led by the team's qualitative methodologist, was conducted on the focus groups, in conjunction with the individual healthcare provider interviews, in order to ensure saturation (Saldaña, 2015).

4.3.3. Site observation

The site observations, as part of Phase 2, aimed to provide in-depth information on the treatment of patients. These observations were conducted at the three research sites during the weekly team meetings of the multidisciplinary healthcare providers. Informed consent was obtained by all attending healthcare providers. Research assistants (who were trained by the research team), as well as a member of the research team (with expertise in research data collection) attended and took detailed notes at the healthcare providers' weekly meetings, at which all patients on the unit were discussed. An observation grid was used to guide the notes taken (see

Observation Grid Appendix B.3). Notes were also combined and reviewed after each meeting by the research team in order to ensure they were accurate. The observations were also sent via email to the healthcare providers for their input and corrections. The observations resulted in gaining an understanding of how the various healthcare providers treating patients were involved in various parts/functions of the transition process, including the level of care needed by a patient, as well as their current medical status, medication packaging, diet type, and functional/cognition ability.

4.3.4. Other sources of data

During the second phase, prospective case study methods were used, in which a patient and caregiver was considered one case and data were collected about them from various sources. The inclusion criteria were frail patients being treated in the targeted research sites, who were expected to transition to a private home in the community, where they would live with at least one family caregiver. A sample of six cases (two participants per case), with two cases per research site, was chosen as appropriate given that within a case study approach the depth of information obtained is the goal (Creswell & Creswell, 2017). Healthcare providers at the targeted research sites, within the circle of care of the patients, approached those patients and their caregivers about interest in participation. If the patient and caregiver consented, their contact information was forwarded to the Research Nurse, who would then seek informed consent. The data, all collected by the trained Research Nurse, included demographic information, patient medical information, pre- and post- discharge interviews, as well as home visit interviews, standardized measures, including those for clinical frailty, cognitive impairment, depression, activities of daily living, ability to perform self-care, apathy, resilience, comorbidity, and health care utilization (see Appendices B.4, B.5, and B.6). The data were used to monitor patients' transition processes in testing the FRAM model. The data collected from home observations, for instance, helped identify the output of functions, such as <identify physical problems>, <identify cognitive problems>, and <identify common issues> when patients are at home.

4.4. Results

The results of this study are presented in the three following subsections to satisfy the objectives of the study, which are shown in the three last columns of Table 4.1. The first subsection presents the constructed comprehensive model of the transition process (the first objective of this study). The results of testing the model to monitor patients' transition processes are shown in the second subsection to meet the second objective. The third subsection indicates the challenges of the transition process to address the third objective of this study.

4.4.1. Constructing the FRAM model

In this subsection, we explain how the FRAM model of the hospital-to-home transition process for frail patients was constructed. To this end, functions were identified, described, and linked together. Identifying and describing functions was an iterative process with several revisions and additions happening across the analysis process. The identified functions were discussed to construct the FRAM model before linking together using the six aspects of the functions. In the step of identifying functions, first, the core functions (those that represent the main activities in the transition process) were identified based on the opinions of healthcare providers (work-as-imagined) reflected in semi-structured interviews. We started by describing the boundary of the system under investigation. The authors agreed that the transition process began with admission to hospital, and moved through discharge from hospital, follow-ups outside of hospital, and readmission to hospital. The functions were identified from the point of admission to the point of readmission including the activities that occur within the defined system boundary. Then, caregivers' and patients' perspectives and patient observations (work-as-observed) were used to recognize more functions. The functions described by healthcare providers (work-as-imagined) and functions identified based on patient observations (work-as-observed) were needed to construct the comprehensive FRAM model.

The comprehensive model was different from the imagined practice as patient observation (work-as-observed) contributed to identifying functions related to patient readmission. In total, the comprehensive model consisted of 38 functions containing both pre-discharge and post-discharge stages. The information gained from healthcare providers and patients/caregivers was employed to characterize the aspects of the functions. Functions were coupled through the aspects of various functions with the same value. The data from focus groups were used to improve the constructed model by adding more functions, adding more details to the description of each function, and finding new couplings or dependencies between functions. The comprehensive FRAM-based model is depicted in Figure 4.2. It was constructed by the FMV.

As indicated in Figure 4.2, the functions were classified into five categories: admission; assessment; synthesis; decision-making; and readmission. The figure indicates that 10 functions were involved in the admission category, and 12 functions accounted for the assessment category. Synthesis and decision-making categories included five functions each. Finally, six functions constituted the readmission category. As illustrated in Figure 4.2, the functions associated with the admission category describe the process of admitting a patient in a geriatric unit. Assessment-related functions indicate how a wide spectrum of healthcare providers, encompassing geriatricians, pharmacists, nurses, therapists, and dietitians work together to deliver treatment to frail patients. Some meetings, such as weekly team meetings and family conferences, are convened to synthesize functions related to the perspectives of healthcare providers and family members/caregivers. Weekly team meetings refer to communication among care team members about patients, and family conferences include communication between the team members and patients/caregivers. The functions associated with the synthesis category investigated patients' health situation before discharge. Decision-related functions determined when there would be a recommendation for a patient to be discharged from the hospital. The care team also recommended which options were appropriate for patients based on the patients' health and financial conditions. In this regard, the patients' level of family support was also of great importance. The care team recommendations for discharge contained patients' and caregivers' opinions as well. The last category of functions describes how and why a patient might be readmitted to hospital.

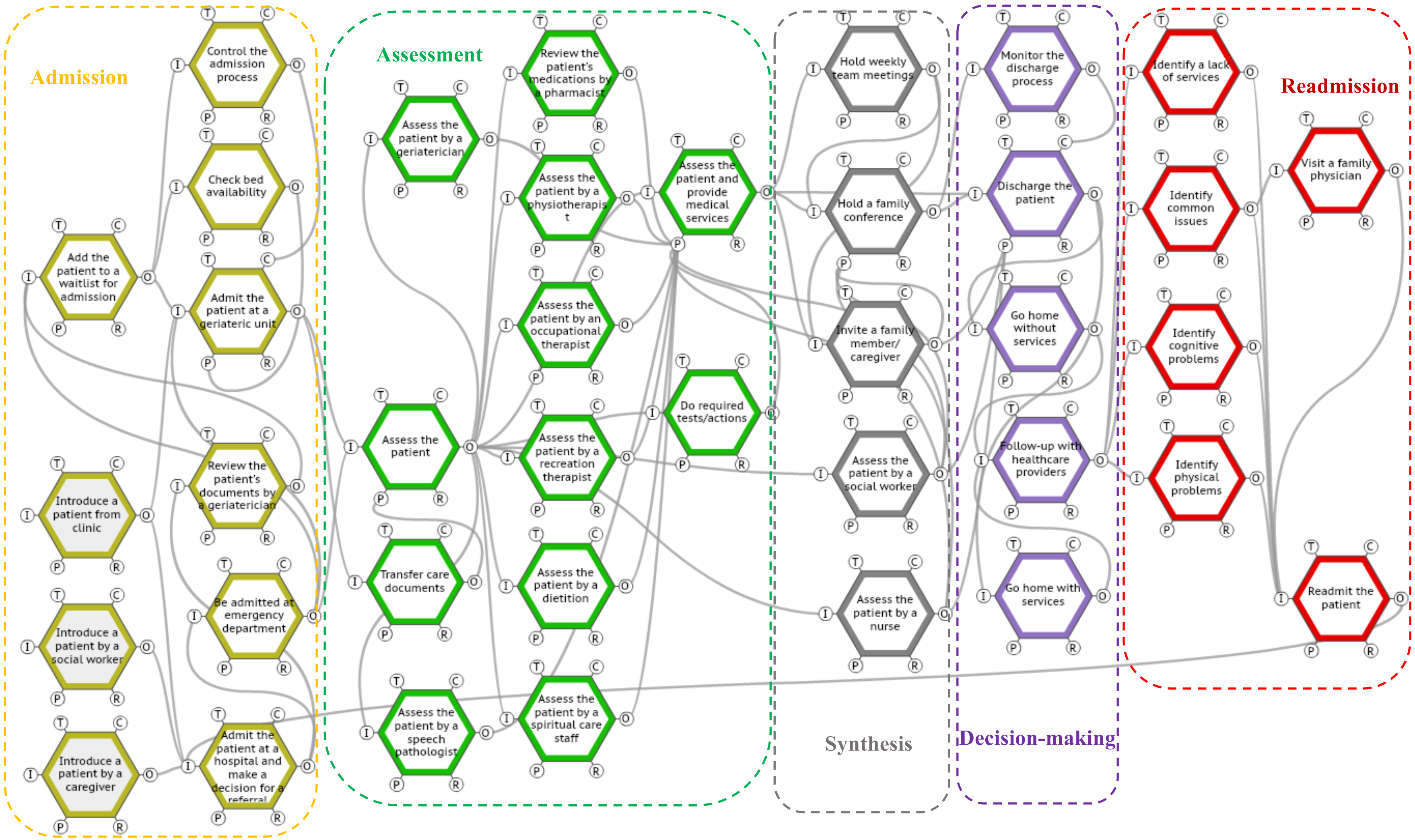

Figure 4.2: The comprehensive FRAM model of the hospital-to-home transition process for frail older patients.

4.4.2. Testing the FRAM model in practice

After constructing the model, it was tested. The objective of testing the FRAM model was to monitor patients' transitions and to learn about the role of active functions involved in the transition process. We exercised the model separately for each of six frail patients in the customized version of the FRAM.

One scenario per patient was defined. Two of these scenarios are presented in Table 4.3 and Appendix B.7 to illustrate. As shown in Table 4.3, each scenario included the number of active functions, the time required for execution of each active function, the output(s) of each active function, downstream coupled function, and coupled function aspects. Then, the comprehensive model and different scenarios were imported into the customized version of the FRAM. The outcome of running the customized version of the FRAM provided a visual representation of what happened for the patient over the course of their transition process. Two examples of the outcomes for two patients are presented in Figure 4.3 and Appendix B.8. Figure 4.3 shows a general view of the environment of the customized version of the FRAM and what happened for patient 3 of city 1, including 18 active functions involved in the transition process from hospital to home. It also provides the real output of each function, and couplings/dependencies between active functions. For instance, the output of the function <Assess the patient by a physiotherapist> was "home exercise", which served as a precondition for function <Assess the patient and provide medical services> (Figure 4.3).

Table 4.3: The information of a scenario provided for patient 3 of city 1.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Fractured hip/Delirium	6	I
2	6	Referral to a geriatrician	5	I
3	5	Dementia/delay	7	I
14	7	Almost 12 days	8	I
26	8	Hospitalizing in geriatric unit	22	I
27	22	Fractured hip/Delirium	35	I
28	22	Nurse assessment	2	I
29	2	Information on dementia	35	P
30	22	SW assessment	11	I
31	11	Social Development Financial Assistance Program	35	P
32	22	Pharmacist assessment	29	I
33	29	Medication reconciliation	35	P
34	22	Physiotherapy	1	I
35	1	Home exercise	35	P
36	22	Occupational therapy	21	I
37	21	Home care services	35	P
38	22	Recreation therapy	23	I
39	23	Cognitive impairment (Dementia)	35	P
40	22	Nutrition therapy	24	I
41	24	Satisfactory	35	P
42	35	Medication change/Home care services/Home exercise/Safety equipment	9	I
43	9	Informing for family conference	0	I
44	9	Informing for discharge	26	I
45	26	Husband	0	P
46	0	Acceptable ability for discharge	4	I
47	4	Arranged for one month later	14	I
48	4	Home care services/delay/no discharge planner (social worker)	3	I
52	14	The physician appointment was performed	3	I

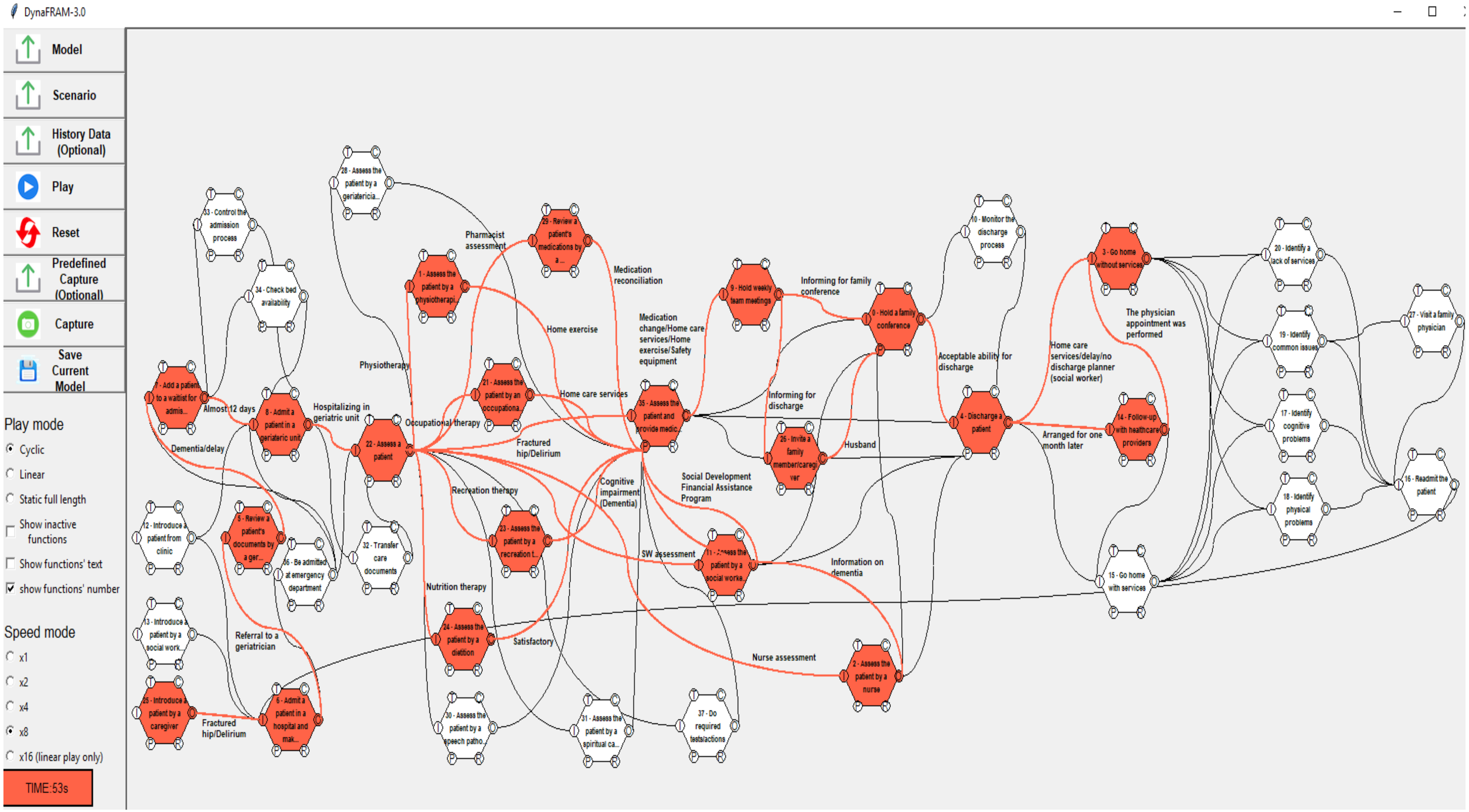

Figure 4.3: An example of a successful outcome (patient 3 from city 1).

This study assumed two criteria to monitor patients' transition processes based on the perspectives of both healthcare providers and patients/caregivers. The first criterion is related to patients' health and ability to return home in the community. This means that the patient has the capacity to live at home and perform daily activities, with or without caregivers and equipment. To this end, the scores obtained by standardized measures, such as clinical frailty, cognitive impairment, and physical self-maintenance were used. Family support is important regarding the first criterion as well. The first criterion can be reflected as the output of the function <Hold a family conference> and is recommended by the care team (healthcare providers) before holding the family conference. For example, Figure 4.3 shows that patient 3 from city 1 was healthy enough for discharge. She had her family support, encompassing her husband and daughter. The second criterion is that the patient is not readmitted to the hospital for the same reason as admission. Appendix B.8 shows that patient 2 from city 3 was readmitted for one of the same reasons as admission. One of the reasons for admission and readmission was "congestive heart failure". Hence, the monitored patient experienced an unsuccessful transition based on the criteria of a hospital readmission. The process ended in the function <Readmit the patient>. On the other hand, Figure 4.3 indicates that the experience of patient 3 from city 1 was successful as the patient was healthy enough to go home and stay there. The transition process of the patient ended in the function <Go home without services>. Table 4.4 shows a summary of the results of running the FRAM model for six patients, including the patient's situation and admission/readmission reasons. According to Table 4.3, five patients (83%) experienced a successful transition, and one patient (17%) had an unsuccessful experience. A fuller version of the results is presented in Appendix B.9, which is used for analyzing the variability of each function's output(s) and identifying challenges of the transition process.

Table 4.4: The results of running the FRAM model in practice.

Patient's no.	Outcome/Reason
City 1: patient 1	**Successful:** Excellent ability during discharge process. Readmission with a different reason (admission reasons: stroke and possible dementia, readmission reason: cough).
City 1: patient 3	**Successful:** Acceptable ability and health during discharge process. Staying at home (admission reasons: fractured hip and delirium, no readmission).
City 2: patient 1	**Successful:** Acceptable ability and health during discharge process. Staying at home (admission reasons: fractured left ankle and fracture of left distal tibia, no readmission).
City 2: patient 2	**Successful:** Acceptable ability and health during discharge process. Staying at home (admission reason: right MCA stroke with left sided weakness, no readmission).
City 3: patient 1	**Successful:** Acceptable ability and health during discharge process. Staying at home (admission reason: dysmobility, no readmission).
City 3: patient 2	**Unsuccessful:** Relatively stable situation during discharge process. Readmission with the same reason as admission (admission reason: fractured pelvis and congestive heart failure, readmission reason: congestive heart failure.

4.4.3. Challenges of the transition process

As mentioned earlier in Subsection 4.4.2, the comprehensive model of the transition process provided in Figure 4.2 was imported into the customized version of the FRAM and run six times for six patients/instantiations (one scenario per patient). The results of running the model helped map each patient's situation and recognize core functions contributing to the transition process for each patient (Figure 4.3 and Appendix B.8). The figures presented in Figure 4.3 and Appendix B.8 show the outputs of the functions involved in transition processes of two patients. The variability in the outputs of core functions within the six instantiations/patients was extracted from the results of running the model and is presented in Appendix B.9. According to the appendix, the variability of each function was described in terms of time and precision for each patient. This subsection explains challenges of the transition process by highlighting similarities and differences between patients' experiences, and using the variability observed in core functions. The similarities and differences are highlighted based on the functions involved in transition processes and the interactions/dependencies between them.

4.4.3.1. Waitlist in admission process to the geriatric unit

In the transition process, in-patients of an acute care unit are placed on a wait list to be transferred into a specialized geriatric unit. It is noteworthy that the waitlist is not associated with admission to hospitals. Patients are receiving hospital care prior to being admitted to geriatric units. The output of function <Add a patient to the waitlist for admission> was identified for each patient. The variability observed in the output of the function was described based on time/duration for each patient in Appendix B.9. The results of the observed variability indicated that time/duration of the waitlist was different for the six patients. Three patients experienced a 12-day waitlist in the admission process into the geriatric unit (50%), one patient experienced a five-day waitlist (17%), and another patient was on the waitlist just one day (17%). Another patient was hospitalized directly at the emergency department as an urgent case.

4.4.3.2. The necessity of team-based care in patient assessment

Team-based care could make a difference for patients in the hospital-to-home transition process by enhancing quality assessment and providing medical services. In the FRAM model provided in Figure 4.2, the function <Assess the patient and provide medical services> along with its preconditions were considered to describe patients' assessment and the provision of required medical services. When all assessments and in-hospital therapies are complete, the physician comes to see the patient and calls for a family conference. The healthcare providers recommend therapies, medication and equipment for patients. The preconditions of the function included patients' assessment by a team of healthcare providers, such as medical doctors, geriatricians, nurses, social workers, and therapists. The full list of team care members is observable in the functions related to assessment category in Figure 4.2. The output(s) of the function <Assess the patient and provide medical services> was identified and presented in Appendix B.9. According to the data, a diverse list of tests and services was provided for each patient in order to improve the patient's ability and health before discharge. The variability in the output of the function provided in Appendix B.9 indicates that various tests like x-ray, blood & sugar tests, and anemia tests were done. Moreover, different types of care, such as physiotherapy, occupational therapy, nutrition therapy, and spiritual care, were provided, however they were dependent on patient need and availability in different hospitals. The data (Appendix B.9) shows a range of healthcare providers (medical doctor, nurse, social worker, and therapists) in the form of the care team worked together to provide appropriate patient care. Some examples from the focus group data confirm the importance of a multidisciplinary team approach to care in the transition process. For instance, in the first phase of data collection (focus group of City 1), a geriatrician mentioned “everybody here has a valuable role in the team, and we all see it, share it and we learn from each other.” The geriatrician added “… but it [a full comprehensive geriatric evaluation] is very much an interdisciplinary assessment, all team members basically do an intake when the patients admitted …”.

4.4.3.3. Lack of discharge planner

A patient will be discharged if the outcome of the function <Hold family conference> shows that the patient is healthy enough, has the financial capacity or funding for services, services are available, as well as family support. The function <Discharge a patient> describes the activities associated with discharging a patient. The family conference is helpful because family members are invited to hear the recommendations from all healthcare providers. Tracking the output of the function <Discharge a patient> indicates that the presence of the discharge planner was variable. Appendix B.9 shows that there was a Registered Nurse discharge planner during the discharge process of two patients (33%) (city 3: patients 1 and 2). A case coordinator played the role of discharge planner for the two patients of city 2 (33%), and a social worker who played the role for the two patients of city 1 (33%). The results indicated that there was no dedicated discharge planner in 66% of the investigated cases, even though case coordinators and social workers performed all or parts of the responsibilities of a discharge planner in transferring the information related to recommendations and services to caregivers/patients for post-discharge process.

4.4.3.4. Financial concerns/limitations for services at home

According to the data (Appendix B.9), the care team recommended some services, such as homemakers or equipment, to improve patients' ability at home, but some patients had difficulties acquiring them. The difficulties included financial limitations, the lack of access to services, and delays in acquiring services. The analysis of the outputs of the functions <Hold family conference> and <Discharge a patient> shows that three patients had recommendations by the healthcare providers to acquire services at home after discharge. Two of them did not follow the recommendations due to a variety of reasons, including financial concerns. Another patient agreed to go home with limited services because of financial limitations. The patient/family agreed to have a paid care provider help them during the day as a part of recommended services for staying at home. The rest of the patients were not asked to acquire any services after discharge, or there was no information in this regard. Both healthcare providers and patients/caregivers confirmed there were financial issues for some of the patients and their family in acquiring the recommended services. A geriatrician highlighted that "I guess the amount of support they [patients] have, like a big limitation is the cost for services." The geriatrician added "a lot of times at the family conference we'll recommend some services, but once they [patients and their family] hear about the amount that they'll have to pay for them, often the family will say "well, we'll try to manage without"." A caregiver mentioned "There's also a big financial component. My parents live on the edge of poverty." An occupational therapist pointed out in a focus group that "And often the financial cost of homemakers or home supports or equipment is too much. People will go home;

they'll take all the free services they can get. And then it'll get time to pay for services, and they can't pay for those services, and they'll cancel all services."

4.4.3.5. The importance of follow-up plans

A successful transition process should have a follow-up plan. As a caregiver pointed out, "that [follow-up] should be part of transitional care, to make sure people go home with as much ability, cognitive and physical, as possible." A nurse manager added in a focus group that "the transition may go really well for a while. But if the follow up doesn't happen then it tends to drop off, so if they're seeing the geriatrician again it will help with the successful transition." The function <Follow up with healthcare providers> describes the follow-up plan, which is used to track patients' health conditions after discharge in order to reduce the probability of readmission. A dietitian confirmed the significance of the follow up plan: "… it [follow up] seems to be lacking because that's where you see people getting readmitted with the same problems." The output of the function <Discharge a patient> for different patients shows a follow up appointment was arranged with a healthcare provider for all six patients (100%), such as family physicians, medical specialists, and physiotherapists (Appendix B.9). As shown in the appendix, the variability observed in the output of the function <Follow up with healthcare providers> revealed that one patient (17%) did not attend the arranged appointment, whereas four of the patients (66%) attended the arranged follow-up appointments. In one case (17%), a physiotherapist visited the patient in their home as a part of Extra Mural Program (Appendix B.9). This suggests the importance of follow-up plans in the transition process of frail older patients after discharge. A dietitian acknowledged this issue in a focus group: "I think that's a big deficit in the discharge planning, like you put a plan in place but then who follows this through to make sure it happens."

4.5. Discussion

4.5.1. The capability of the FRAM for modeling the transition process

The current study employed the FRAM to model and explain the daily activities of the hospital-to-home transition process for frail older adults. The FRAM is an appropriate approach to visualize what happens in a system and to provide a deeper understanding about the system's reality (Hounsgaard, 2016). Ross et al. (2018) used the FRAM to recognize the core functions of healthcare systems. The current study employed the FRAM to identify and classify the functions involved in the transition process of frail older people. The main functions identified in the current study encompassed both the discharge process (Buikstra et al., 2020) and post-discharge step as well. Using a spectrum of perspectives from healthcare providers and patients/caregivers has enriched the comprehensive model provided in the current study in comparison with similar studies. Involving patient observations (work-as-observed) resulted in recognizing the possible reasons of patient readmission. Using different perspectives in formulating the transition process helps cope with the complexity of the transition, as investigated by Aase & Waring (2020).

4.5.2. Monitoring the transition process by the FRAM

One of the most important principles of the FRAM -and resilience engineering- is the equivalence of successes and failures. This means that things that go right and things that go wrong happen in a similar way. Acceptable (and unacceptable) outcomes are due to the ability (and inability) of organizations, groups, and individuals to adapt successfully to expected and unexpected events (Hollnagel, 2017). Monitoring the transition process of frail patients and learning from their experiences provided a context to distinguish a successful transition from an unsuccessful one. The results of the customized version of the FRAM showed that successful and unsuccessful transitions are rooted in a same set of functions. Performance variability in the output of the functions was the main reason for the successful and unsuccessful outcomes, as the results of other studies have emphasized (Kaya et al., 2019; Patriarca et al., 2018).

4.5.3. Challenges of the transition process through the lens of the FRAM

The analysis of the variability observed in functions' outputs revealed that there were some challenges in the transition process of frail patients. One of the challenges was related to the variability associated with the waitlist to be admitted into geriatric units, which might influence the length of the transition process. Managing the variability of the waitlists pertinent to geriatric units is of great importance. Some patients waited longer than others, which may be a reflection of a triage system that allocates services based on needs. The results of other studies showed that the waitlist should be as short as possible (Doyle et al., 2016; Storm et al., 2014). Waiting for different types of services can lead to delays in the discharge process of frail older people (Doyle et al., 2016). As Buikstra et al. (2020) pointed out, a long waitlist affects the discharge plan and leads to a longer discharge process for frail patients. Moreover, long waitlists on admission may lead to increasing problems in taking care of patients and decreasing patient satisfaction (Storm et al., 2014).

A transition process should include team-based care as a main part of patient assessment. The team-based care is used to cope with adverse effects of disruptions and delays in different parts of the transition process, such as admission. It also contributes to success in the transition process and optimization of patient assessment process (Buikstra et al., 2020). Pickup et al. (2017) and Schutijser et al. (2019) also acknowledged that teamwork assists healthcare systems to manage delays in the process of patients' care. The adjustments made by team members are essential for improving patients' care plan, as highlighted by Kianfar et al. (2019). Teamwork is also essential for an appropriate discharge as frail patients have complex needs and their transition process includes different perspectives (Laugaland et al., 2012).

Another finding of the current research showed there was no dedicated discharge planner for the cases/patients on the geriatric units of city 1 and city 2. The results of this study showed that other healthcare professionals, such as social workers (city 1) and case coordinators (city 2) carried out the duties of a discharge planner. Even though discharge planning is not limited to just a discharge planner, their role is to facilitate the discharge step so that patients and caregivers capture the information pertinent to post discharge. Using a discharge planner leads to decreasing the length of staying at hospital (Palmer Jr et al., 2001). Their role facilitates the discharge process and affects the process of designing and implementing the discharge plan for patients (Holland et al., 2015). Discharge planning has significant influences on decreasing readmission rates for frail patients, as pointed out by Laugaland et al. (2012).

Financial concern was a common problem of patients for acquiring the required equipment and services for staying at home after discharge from hospital. It can be a barrier to supply services required for patients (Doyle et al., 2016). The quality of healthcare related services can be affected by cost (Storm et al., 2014). As Laugaland et al. (2014) highlighted, this factor can limit the domain of patients' performance and slow the process of patients' improvement. Healthcare providers are required to be sensitive to all of patients' needs, including their ability to finance and utilize the necessary resources to mobilize and maintain recommendations during the discharge process. An application of the human factors and ergonomics (HFE) approach showed the role of financial concern as a barrier to care quality of frail patients (Holden & Mickelson, 2013).

The last challenge found by the current study was the importance of follow-up plans after discharge from hospital for frail older patients. The influence of discharge planning without follow-up plans is uncertain (Rytter et al., 2010). Unsuccessful transitions can happen due to the lack of follow-up plans as patients may experience adverse events (Storm et al., 2014). As Halasyamani et al. (2006) highlighted, follow-up plans could contribute to risk reduction of readmission of frail older patients after hospital discharge. Other studies confirmed the positive role of follow-up plans in the transition process (Avlund et al., 2002; Laugaland et al., 2014). Follow-up actions are required if healthcare providers discover errors when they review patients' conditions, including services and medications (Kianfar et al., 2019).

The investigation of work-as-done (WAD) and work-as-imagined (WAI) is of great importance, particularly for improving safety in health systems (Deutsch, 2017). The WAI illustrates the ideal state, whereas the WAD is explained by what people actually do (Braithwaite et al., 2016). As explored by the current study, the problems and challenges of the transition process were revealed through studying the WAD and modeling by the FRAM. However, the challenges of health systems, including the transition process, may not only be a problem of malfunction in the WAD dimension, but also the result of a failure in the WAI dimension rooted in health system design in general, as stated by Braithwaite et al. (2016) and Catchpole & Alfred (2018).

4.6. Study limitations and future research directions

This qualitative FRAM-based research examined just six patients in the phase of testing the FRAM model in practice. Although in-depth information was obtained on each case, the small sample size of investigated patients limits the generalizability of the findings of this study. To this end, future studies will take a supplementary step of collecting further patient data in order to expand the scope of this research. Future research could concentrate on performance variability of functions' outputs. This, in turn, allows researchers to calculate the aggregation of variability and to recommend appropriate policies to manage variability in daily operations of the transition process so that frail patients improve the safety and quality of their lives. In the meantime, the generalizability of the results will be reinforced due to more diversity and number of frail patients.

As exposed in the time of the COVID-19 pandemic, the efficiency of healthcare systems is low, and costs are high. Future research could also focus on the formulation and development of public health policies for frail older people during hospital to home transitions, which may affect the performance of the healthcare system as a whole. Moreover, trade-offs between efficiency and thoroughness, known as the ETTO principle, could be investigated in the future. Requirements, including resources, should be met to achieve acceptable performance to ensure system operation (Hollnagel, 2009). The focus will be on researching the trade-off between acceptable (or unacceptable) performance and meeting requirements and current conditions to interpret why things that go right sometimes go wrong. Investigating differences between work-as-done and work-as-imagined has a great potential for future research. The possible gap between protocols and procedures of the transition process (work-as-imagined) and observations of patients' transitions (work-as-done) will be a basis to improve the quality of care during the transition process for frail patients.

4.7. Conclusions

The hospital to home transition process is a complex procedure covering admission, assessment, treatment, discharge, and follow up of patients. The process links hospital, home, and community to enhance patients' health and safety. This research proposed a FRAM-based approach to model and analyze the complexity of everyday activities in the transition process of frail patients and examined six cases across three hospitals. A wide range of perspectives, including healthcare providers, patients, and caregivers were involved in the modeling step to address the complexity of the process. The comprehensive model presented in this study enabled the research team to better understand daily operations in the care of frail older adults during transitions. The model covered the admission process, patient assessment and treatment, the discharge process, follow-up plans, and readmission. The results of this study revealed how variability in the outputs of everyday activities/functions resulted in adversities for patients in the healthcare system. The conditions of the waitlist, team-based care, discharge planners, financial concerns, and follow-up plans should be monitored and improved to deal with the adversities of the transition process. The outcomes found in this research will help healthcare providers and decision makers identify and manage the strengths and weaknesses of such transitions for patients' health enhancement.

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References

Aase, K., & Waring, J. (2020). Crossing boundaries: Establishing a framework for researching quality and safety in care transitions. *Applied Ergonomics*, *89*, 103228.

Avlund, K., Jepsen, E., Vass, M., & Lundemark, H. (2002). Effects of comprehensive follow-up home visits after hospitalization on functional ability and readmissions among old patients. A randomized controlled study. *Scandinavian Journal of Occupational Therapy*, *9*(1), 17–22.

Barnhart, S. L., & Carpenter, A. (2016). Transition from hospital to home. In *Caring for the Ventilator Dependent Child* (pp. 89–119). Springer.

Bjerga, T., Aven, T., & Zio, E. (2016). Uncertainty treatment in risk analysis of complex systems: The cases of STAMP and FRAM. *Reliability Engineering & System Safety*, *156*, 203–209.

Braithwaite, J., Wears, R. L., & Hollnagel, E. (2016). *Resilient health care, volume 3: Reconciling work-as-imagined and work-as-done*. CRC Press.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101.

Bridges, K. E., Corballis, P. M., & Hollnagel, E. (2018). “Failure-to-Identify” Hunting Incidents: A Resilience Engineering Approach. *Human Factors*, *60*(2), 141–159.

Buikstra, E., Strivens, E., & Clay-Williams, R. (2020). Understanding variability in discharge planning processes for the older person. *Safety Science*, *121*, 137–146.

Campbell-Sills, L., & Stein, M. B. (2007). Psychometric analysis and refinement of the connor–davidson resilience scale (CD-RISC): Validation of a 10-item measure of resilience. *Journal of Traumatic Stress: Official Publication of The International Society for Traumatic Stress Studies*, *20*(6), 1019–1028.

Canadian Frailty Network (2020). Frailty matters.

Catchpole, K., & Alfred, M. (2018). Industrial conceptualization of health care versus the naturalistic decision-making paradigm: Work as imagined versus work as done. *Journal of Cognitive Engineering and Decision Making*, *12*(3), 222–226.

Charlson, M. E., Pompei, P., Ales, K. L., & MacKenzie, C. R. (1987). A new method of classifying prognostic comorbidity in longitudinal studies: development and validation. *Journal of Clinical Epidemiology*, *40*(5), 373–383.

Clay-Williams, R., Hounsgaard, J., & Hollnagel, E. (2015). Where the rubber meets the road: using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines. *Implementation Science*, *10*(1), 125.

Connor, K. M., & Davidson, J. R. T. (2003). Development of a new resilience scale: The Connor-Davidson resilience scale (CD-RISC). *Depression and Anxiety*, *18*(2), 76–82.

Cosco, T. D., Kaushal, A., Richards, M., Kuh, D., & Stafford, M. (2016). Resilience measurement in later life: a systematic review and psychometric analysis. *Health and Quality of Life Outcomes*, *14*(1), 16.

Creavin, S. T., Wisniewski, S., Noel-Storr, A. H., Trevelyan, C. M., Hampton, T., Rayment, D., Thom, V. M., Nash, K. J. E., Elhamoui, H., & Milligan, R. (2016). Mini-Mental State Examination (MMSE) for the detection of dementia in clinically unevaluated people aged 65 and over in community and primary care populations. *Cochrane Database of Systematic Reviews*, *1*.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.

Damen, N. L., de Vos, M. S., Moesker, M. J., Braithwaite, J., van Wijngaarden, R. A. F. de L., Kaplan, J., Hamming, J. F., & Clay-Williams, R. (2019). Preoperative anticoagulation management in everyday clinical practice: an international comparative analysis of work-as-done using the functional resonance analysis method. Journal of Patient Safety, 17(3), 157-165.

Deutsch, E. S. (2017). Bridging the gap between work-as-imagined and work-as-done. *Pennsylvania Patient Safety Advisory*, *14*(2), 80–83.

Doyle, J., Caprani, N., Kealy, A., Bond, R., Komaba, Y., & Inomata, A. (2016). Healthcare professionals views on technology to support older adults transitioning from hospital to home. *Proceedings of the 30th International BCS Human Computer Interaction Conference 30*, 1–11.

Ebrahimi, Z., Wilhelmson, K., Eklund, K., Moore, C. D., & Jakobsson, A. (2013). Health despite frailty: exploring influences on frail older adults' experiences of health. *Geriatric Nursing*, *34*(4), 289–294.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198.

Fried, L. P., Tangen, C. M., Walston, J., Newman, A. B., Hirsch, C., Gottdiener, J., Seeman, T., Tracy, R., Kop, W. J., & Burke, G. (2001). Frailty in older adults: evidence for a phenotype. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *56*(3), M146–M157.

Goins, R. T., Gregg, J. J., & Fiske, A. (2013). Psychometric properties of the Connor-Davidson resilience scale with older American Indians: The native elder care study. *Research on Aging*, *35*(2), 123–143.

Halasyamani, L., Kripalani, S., Coleman, E., Schnipper, J., Van Walraven, C., Nagamine, J., Torcson, P., Bookwalter, T., Budnitz, T., & Manning, D. (2006). Transition of care for hospitalized elderly patients—development of a discharge checklist for hospitalists. *Journal of Hospital Medicine*, *1*(6), 354–360.

Heuberger, R. A. (2011). The frailty syndrome: a comprehensive review. *Journal of Nutrition in Gerontology and Geriatrics*, *30*(4), 315–368.

Hill, R., & Hollnagel, E. (2016). *Instructions for use of the FRAM Model Visuliser (FMV)*.

Holden, R. J., Carayon, P., Gurses, A. P., Hoonakker, P., Hundt, A. S., Ozok, A. A., &

Rivera-Rodriguez, A. J. (2013). SEIPS 2.0: a human factors framework for studying and improving the work of healthcare professionals and patients. *Ergonomics*, *56*(11), 1669–1686.

Holden, R. J., & Mickelson, R. S. (2013). Performance barriers among elderly chronic heart failure patients: An application of patient-engaged human factors and ergonomics. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *57*(1), 758–762.

Holland, D. E., Conlon, P. M., Rohlik, G. M., Gillard, K. L., Messner, P. K., & Mundy, L. M. (2015). Identifying hospitalized pediatric patients for early discharge planning: A feasibility study. *Journal of Pediatric Nursing*, *30*(3), 454–462.

Hollnagel, E. (2009). *The ETTO principle: efficiency-thoroughness trade-off: why things that go right sometimes go wrong*. Ashgate Publishing, Ltd.

Hollnagel, E. (2012). *FRAM, the functional resonance analysis method: modelling complex socio-technical systems*. Ashgate Publishing, Ltd.

Hollnagel, E. (2017). *FRAM: the functional resonance analysis method: modelling complex socio-technical systems*. CRC Press.

Hollnagel, E., & Braithwaite, J. (2019). *Resilient health care*. CRC Press.

Hounsgaard, J. (2016). *Patient Safety in Everyday Work: Learning from things that go right*. Syddansk Universitet.

Katz, J. N., Chang, L. C., Sangha, O., Fossel, A. H., & Bates, D. W. (1996). Can comorbidity be measured by questionnaire rather than medical record review? *Medical Care*, 73–84.

Kaya, G. K., Ovali, H. F., & Ozturk, F. (2019). Using the functional resonance analysis method on the drug administration process to assess performance variability. *Safety Science*, *118*, 835–840.

Kianfar, S., Carayon, P., Hundt, A. S., & Hoonakker, P. (2019). Care coordination for chronically ill patients: identifying coordination activities and interdependencies. *Applied Ergonomics*, *80*, 9–16.

Laugaland, K., Aase, K., & Barach, P. (2012). Interventions to improve patient safety in transitional care–a review of the evidence. *Work*, *41*(Supplement 1), 2915–2924.

Laugaland, K., Aase, K., & Waring, J. (2014). Hospital discharge of the elderly-an observational case study of functions, variability and performance-shaping factors. *BMC Health Services Research*, *14*(1), 365.

Lawton, M. P., & Brody, E. M. (1969). Assessment of older people: self-maintaining and instrumental activities of daily living. *The Gerontologist*, *9*(3_Part_1), 179–186.

Macchi, L., Hollnagel, E., & Leonhard, J. (2009). *Resilience Engineering approach to safety assessment: an application of FRAM for the MSAW system.*

McNab, D., Freestone, J., Black, C., Carson-Stevens, A., & Bowie, P. (2018). Participatory design of an improvement intervention for the primary care management of possible sepsis using the Functional Resonance Analysis Method. *BMC Medicine*, *16*(1), 174.

Nuernberger, K., Atkinson, S., & MacDonald, G. (2018). Seniors in Transition: Exploring Pathways Across the Care Continuum. *Healthcare Quarterly*, *21*(1).

O'Hara, J. K., Baxter, R., & Hardicre, N. (2020). 'Handing over to the patient': A FRAM analysis of transitional care combining multiple stakeholder perspectives. *Applied Ergonomics*, *85*, 103060.

Oeppen, J., & Vaupel, J. W. (2004). Demography. Broken limits to life expectancy. Science of human ageing. *FEBS Lett*, *571*, 243–247.

Organization, W. H. (2015). *World report on ageing and health*. World Health Organization.

Palmer Jr, H. C., Armistead, N. S., Elnicki, D. M., Halperin, A. K., Ogershok, P. R., Manivannan, S., Hobbs, G. R., & Evans, K. (2001). The effect of a hospitalist service with nurse discharge planner on patient care in an academic teaching hospital. *The American Journal of Medicine*, *111*(8), 627–632.

Patriarca, R., & Bergström, J. (2017). Modelling complexity in everyday operations: functional resonance in maritime mooring at quay. *Cognition, Technology &*

Work, *19*(4), 711–729.

Patriarca, R., Di Gravio, G., & Costantino, F. (2017). A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. *Safety Science*, *91*, 49–60.

Patriarca, R., Falegnami, A., Costantino, F., & Bilotta, F. (2018). Resilience engineering for socio-technical risk analysis: Application in neuro-surgery. *Reliability Engineering & System Safety*, *180*, 321–335.

Pereira, A. G. (2013). *Introduction to the Use of FRAM on the effectiveness assessment of a radiopharmaceutical Dispatches process*.

Pickup, L., Atkinson, S., Hollnagel, E., Bowie, P., Gray, S., Rawlinson, S., & Forrester, K. (2017). Blood sampling-Two sides to the story. *Applied Ergonomics*, *59*, 234–242.

Praetorius, G., Hollnagel, E., & Dahlman, J. (2015). Modelling Vessel Traffic Service to understand resilience in everyday operations. *Reliability Engineering & System Safety*, *141*, 10–21.

Raben, D. C., Viskum, B., Mikkelsen, K. L., Hounsgaard, J., Bogh, S. B., & Hollnagel, E. (2018). Application of a non-linear model to understand healthcare processes: using the functional resonance analysis method on a case study of the early detection of sepsis. *Reliability Engineering & System Safety*, *177*, 1–11.

Randriambelonoro, M., Perrin, C., Blocquet, A., Kozak, D., Fernandez, J. T., Marfaing, T., Bolomey, E., Benhissen, Z., Frangos, E., & Geissbuhler, A. (2020). Hospital-to-Home Transition for Older Patients: Using Serious Games to Improve the Motivation for Rehabilitation–a Qualitative Study. *Journal of Population Ageing*, 1–19.

Rennke, S., Nguyen, O. K., Shoeb, M. H., Magan, Y., Wachter, R. M., & Ranji, S. R. (2013). Hospital-initiated transitional care interventions as a patient safety strategy: a systematic review. *Annals of Internal Medicine*, *158*(5_Part_2), 433–440.

Resnick, B., Zimmerman, S. I., Magaziner, J., & Adelman, A. (1998). Use of the

Apathy Evaluation Scale as a measure of motivation in elderly people. *Rehabilitation Nursing*, *23*(3), 141–147.

Robinson, C. A., Bottorff, J. L., Lilly, M. B., Reid, C., Abel, S., Lo, M., & Cummings, G. G. (2012). Stakeholder perspectives on transitions of nursing home residents to hosRobinson, C. A., Bottorff, J. L., Lilly, M. B., Reid, C., Abel, S., Lo, M., & Cummings, G. G. (2012). Stakeholder perspectives on transitions of nursing home residents to hospital eme. *Journal of Aging Studies*, *26*(4), 419–427.

Rockwood, K., Song, X., MacKnight, C., Bergman, H., Hogan, D. B., McDowell, I., & Mitnitski, A. (2005). A global clinical measure of fitness and frailty in elderly people. *Cmaj*, *173*(5), 489–495.

Roffman, C., Buchanan, J., & Allison, G. (2016). Charlson comorbidities index. *Journal of Physiotherapy*, *62*(3).

Ross, A., Sherriff, A., Kidd, J., Gnich, W., Anderson, J., Deas, L., & Macpherson, L. (2018). A systems approach using the functional resonance analysis method to support fluoride varnish application for children attending general dental practice. *Applied Ergonomics*, *68*, 294–303.

Rosso, C. B., & Saurin, T. A. (2018). The joint use of resilience engineering and lean production for work system design: a study in healthcare. *Applied Ergonomics*, *71*, 45–56.

Rytter, L., Jakobsen, H. N., Rønholt, F., Hammer, A. V., Andreasen, A. H., Nissen, A., & Kjellberg, J. (2010). Comprehensive discharge follow-up in patients' homes by GPs and district nurses of elderly patients: A randomized controlled trial. *Scandinavian Journal of Primary Health Care*, *28*(3), 146–153.

Saldaña, J. (2015). *The coding manual for qualitative researchers*. Sage.

Salehi, V., Veitch, B., & Smith, D. (2021). Modeling complex socio-technical systems using the FRAM: A literature review. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *31*(1), 118–142.

Saurin, T. A., & Werle, N. J. B. (2017). A framework for the analysis of slack in socio-technical systems. *Reliability Engineering & System Safety*, *167*, 439–451.

Schutijser, B. C. F. M., Jongerden, I. P., Klopotowska, J. E., Portegijs, S., de Bruijne, M. C., & Wagner, C. (2019). Double checking injectable medication administration: Does the protocol fit clinical practice? *Safety Science*, *118*, 853–860.

Sheikh, J. I., & Yesavage, J. A. (1986). Geriatric Depression Scale (GDS): recent evidence and development of a shorter version. *Clinical Gerontologist: The Journal of Aging and Mental Health*.

Smith, D., Veitch, B., Khan, F., & Taylor, R. (2020). Integration of Resilience and FRAM for Safety Management. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *6*(2), 4020008.

Storm, M., Siemsen, I. M. D., Laugaland, K., Dyrstad, D. N., & Aase, K. (2014). Quality in transitional care of the elderly: Key challenges and relevant improvement measures. *International Journal of Integrated Care*, *14*.

Tian, J., Wu, J., Yang, Q., & Zhao, T. (2016). FRAMA: a safety assessment approach based on Functional Resonance Analysis Method. *Safety Science*, *85*, 41–52.

Williams, S., Nolan, M., & Keady, J. (2009). Relational practice as the key to ensuring quality care for frail older people: discharge planning as a case example. *Quality in Ageing and Older Adults*, *10*(3), 44.

Chapter 5

A reinforcement learning development of the FRAM for functional reward-based assessments of complex systems performance*

Co-authorship statement. A version of this chapter has appeared in the *International Journal of Industrial Ergonomics* published by *Elsevier*. The lead author, Vahid Salehi, has generated the model, implemented the algorithm, and designed the scenarios for running the model. The co-author Trung Tien Tran programmed the reinforcement learning part. The research data gathered by a research team from University of New Brunswick were used for modelling the system. Dr. Natasha Hanson from University of New Brunswick led the data collection process. The co-author Dr. Doug Smith contributed to shaping the interview questions to get the data we used to build the model. Co-authors Prof. Brian Veitch and Dr. Doug Smith supervised the study. All authors read and approved the final draft.

Abstract. Although the Functional Resonance Analysis Method (FRAM) is a well-established approach to visualizing complex systems' operations in terms of functions, further improvements are required to examine systems' performance

* Salehi, V., Tran, T. T., Veitch, B., & Smith, D. (2022). A reinforcement learning development of the FRAM for functional reward-based assessments of complex systems performance. *International Journal of Industrial Ergonomics*, *88*, 103271. https://doi.org/10.1016/j.ergon.2022.103271

through functionality. This study aims to develop an approach to couple the FRAM to reinforcement learning (RL) to explore complex operations. The developed approach is called the functional RL approach and constitutes a novel way of using a FRAM model to explore functionality using an artificial agent who responds to reward values assigned to functional parameters. To exemplify the approach, an agent is employed to perform the role of a patient and explore a functional environment generated by the FRAM. Reward values are considered to motivate the agent in order to explore the environment to achieve its objective. The ability of the developed approach is examined using different scenarios implemented in healthcare operations. The results of using the functional RL approach indicate that the approach is able to specify the functional pathway taken by the agent and to examine the performance of the system based on accumulated action value. The outcomes of this study demonstrate that the developed functional RL approach provides a novel means to explore operational environments to identify the pathways that have potential to affect the system performance. This method can be used as a powerful way to assess how a system performs under different management structures.

Keywords: Functional resonance analysis method (FRAM); Functional pathway exploration; Reinforcement learning (RL); Artificial agent; Accumulated action value.

5.1. Introduction

The Functional resonance analysis method (FRAM), developed by Hollnagel (2012), is a function-based approach to generating a descriptive and non-hierarchical model of activities in complex socio-technical systems. The connections between functions are called couplings or dependencies. A FRAM model includes a network of functional couplings (Adriaensen et al., 2021) and presents a perspective to analyze work-as-done in everyday activities (de Souza et al., 2021). FRAM is used to elucidate potential functional pathways in complex operations and to understand the interconnections between different activities of the operations (Doug Smith et al., 2020). It also helps analyze the influence of functional interactions on the outcomes of a system (Kaptan et al., 2021; Slater et al., 2021).

FRAM aims to identify and manage the sources of variability in complex operations (Hollnagel, 2012; Salehi, Smith, et al., 2021). It is a well-designed method to analyze system behaviour based on performance variability (Kim & Yoon, 2021). It relies on systems theory and aims to identify the interactions between system components in order to analyze the ways safe and unsafe interactions might arise (Kaya et al., 2019). The FRAM emphasizes that there is a relationship between functional variability and system performance. That is, upstream functional variability might propagate in the system and affect downstream functional outputs. The aggregation of abnormal functional variations (or functional resonance) might result in undesired outcomes in the entire system and lead to unexpected outcomes, whereas the aggregation of positive functional variations could result in acceptable outcomes (Hollnagel, 2012; Huang et al., 2021; Salehi, Smith, et al., 2021). Variability management proposes amplifying normal or positive variations, while the aggregation of negative variations should be dampened (Hollnagel, 2012b).

A growing number of studies indicate that the FRAM has been employed in a wide spectrum of contexts to pursue different objectives in complex operations of socio-technical systems, such as healthcare, aviation, transportation, maritime, railway, construction, process industries, and environment (Patriarca et al., 2020; Salehi, Veitch, et al., 2021). According to Kim & Yoon (2021), the FRAM was used to help analyze crisis management during COVID-19 pandemic by focusing on hypothetical scenarios related to a disease contaminated case. Critical situations were analyzed, and potential risks were assessed through identifying interactions between functions and sources of variability. The FRAM also has been applied to aviation-related procedures to analyze and understand safety management in the aviation industry. Potential hazardous paths affecting an accident were identified using the FRAM (Hirose et al., 2016). It has revealed the potential of improving safety management in the construction sector. It was employed to capture in-depth information related to daily performance and to identify organizational factors affecting safety (del Carmen Pardo-Ferreira et al., 2020).

An investigation of FRAM-related studies shows that the FRAM has been upgraded by employing supplementary approaches to improve its analytical and computational capability to help analysts and managers with the assessment of complex socio-technical systems (Patriarca et al., 2020; Salehi, Veitch, et al., 2021). As shown in Table 5.1, a diverse range of supplementary approaches were used in the FRAM-related studies to address the shortcomings of the FRAM. Danial et al. (2021) introduced a method, encompassing FRAM and graph theory to detect anomalies in complex socio-technical operations. The outcomes of the study showed that the method can convert FRAM models to graphs and approximate anomalies in the graphs. The introduced method was also able to capture functional differences through pattern matching. Zinetullina et al. (2021) developed an integrated FRAM-Bayesian network approach to quantify resilience in process systems. The developed approach is useful in assessing the level of resilience based on interactions between technical, human, and organizational parts of complex process systems. Huang et al. (2021) combined FRAM with N-K model, the theory of studying organism evolution, to calculate quantitatively the variability of functional modules. The introduced approach facilitates variability evaluation by means of calculating the intensity of coupling risks. Yu et al. (2020) introduced a framework, including the FRAM and rule mining, a machine learning approach, to identify hazards in a complex process system. The complex interactions between different parts of the system were discovered by the FRAM. Additionally, the aggregation of variability was specified. Association rule mining was applied to help interpret rules to identify potential hazard situations. A list of main supplementary approaches that were combined with the FRAM to improve its assessment techniques are presented in Table 5.1.

Table 5.1: Main supplementary methods used to enhance the performance of the FRAM.

Study	Supplementary method	Objective
Current study	Reinforcement learning	System's performance assessment through functional pathway exploration
Kaya et al. (2021)	Monte Carlo simulation method and regression analysis	Measuring variability
Danial et al. (2021)	Graph theory	Anomaly detection
Zinetullina et al. (2021)	Bayesian network	Quantitative resilience assessment
Huang et al. (2021)	N-K model	Variability calculation
Alboghobeish & Shirali (2021)	Analytic hierarchy process (AHP)	Risk management
Yu et al. (2020)	Rule mining (machine learning)	Hazard identification
França et al. (2019)	Analytic hierarchy process (AHP)	Complexity management
Li et al. (2019)	Accident Causation Analysis and Taxonomy (ACAT)	Risk identification
Patriarca et al. (2017)	Monte Carlo simulation method	Performance variability assessment
Patriarca & Bergström (2017)	Abstraction hierarchy	Complexity modelling
Studic et al. (2017)	Grounded theory	Accident investigation
Toroody et al. (2016)	Fault tree	Accident investigation

The FRAM, in its current format, does not have a capability to allow an artificial agent to explore a FRAM model. It is also not possible to identify the pathways that may have potential to influence the system performance. The current study aims to develop an approach to gamify the FRAM to enable an artificial agent to explore a functional environment based on a trail-error policy and a reward system. In order to do so, the FRAM is combined with reinforcement learning, a machine learning technique, to provide a dynamic functional environment for an artificial agent to move in and interact with the environment. The developed approach provides the agent with learning from its reward-based actions.

Machine learning is the development and study of computational algorithms that autonomously learn from data (Salehi et al., 2020). Three main techniques of machine learning are supervised, unsupervised, and reinforcement learning (RL) (Olawoyin & Chen, 2018). RL technique is neither based on supervised learning nor unsupervised learning. It learns to react to an environment on its own. A learning agent tries to move in the environment, interacts with the environment, and learns from the environment by the assignment of reward values. RL deals with exploration and follows a trial-and-error method (Goodfellow et al., 2016). It is an appropriate approach to explore functionality in complex systems where finding data is difficult. A review of relevant literature shows that there are a few appropriate methods regarding pathway exploration/selection. The characteristics of the methods are summarized in Table 5.2. Three main categories of methods are discussed and compared: a) reinforcement learning, b) graph-based approaches, and c) multi-criteria decision-making (MCDM) approaches. As shown in Table 5.2, the RL technique is capable of exploring unknown environments (Goodfellow et al., 2016) whereas graph-based and MCDM approaches are not suitable to explore an unknown environment. The dependency of the RL technique on data and information is less than other approaches discussed in Table 5.2 (Hegedűs et al., 2019). MCDM approaches are data dependent so that less information results in inaccurate outcomes (Liang & Meng, 2019). Another advantage of using RL is to manage probabilistic pathways properly, and randomness can be involved in the process of exploration from the beginning. The capability of learning is a unique characteristic of RL allowing an agent to learn from its experience (Klar et al., 2021). RL technique has been widely employed in different contexts, such as engineering (Klar et al., 2021;

Zhou et al., 2021), business (Song et al., 2021), psychology (Hackel et al., 2020), and healthcare (Coronato et al., 2020; Li et al., 2021). Even though RL has been widely used in various contexts for different purposes, none of them has concentrated on a functional development of the FRAM for pathway exploration in order to identify the pathways that may influence the system performance.

Table 5.2: A brief comparison of pathway exploration approaches.

Method	Unknown environment	Data dependency	Probabilistic (randomness)	Learning ability
Reinforcement learning (machine learning)	Capable	Low	Yes	Yes
Graph-based approaches	Incapable	high	No	No
MCDM approaches	Incapable	Dependent	No	No

The remainder of this manuscript is organized as follows. Section 5.2 includes the structure of this study and explains the RL technique as a complementary approach to the FRAM development. Section 5.3 is devoted to developing the FRAM by means of RL and describing the requirements of using the developed approach in practice. In Section 5.4, the results of applying the functional RL approach to a complex healthcare operation are presented and discussed. The results of sensitivity analysis and weighting functions are also presented and discussed in the section. In Section 5.5, the limitations of this study and an outline of future research are described. In Section 5.6, the major conclusions of this study are presented.

5.2. Background concepts

A schematic structure of this research is presented in Figure 5.1. The FRAM and RL methods used in this study are described in the following subsections.

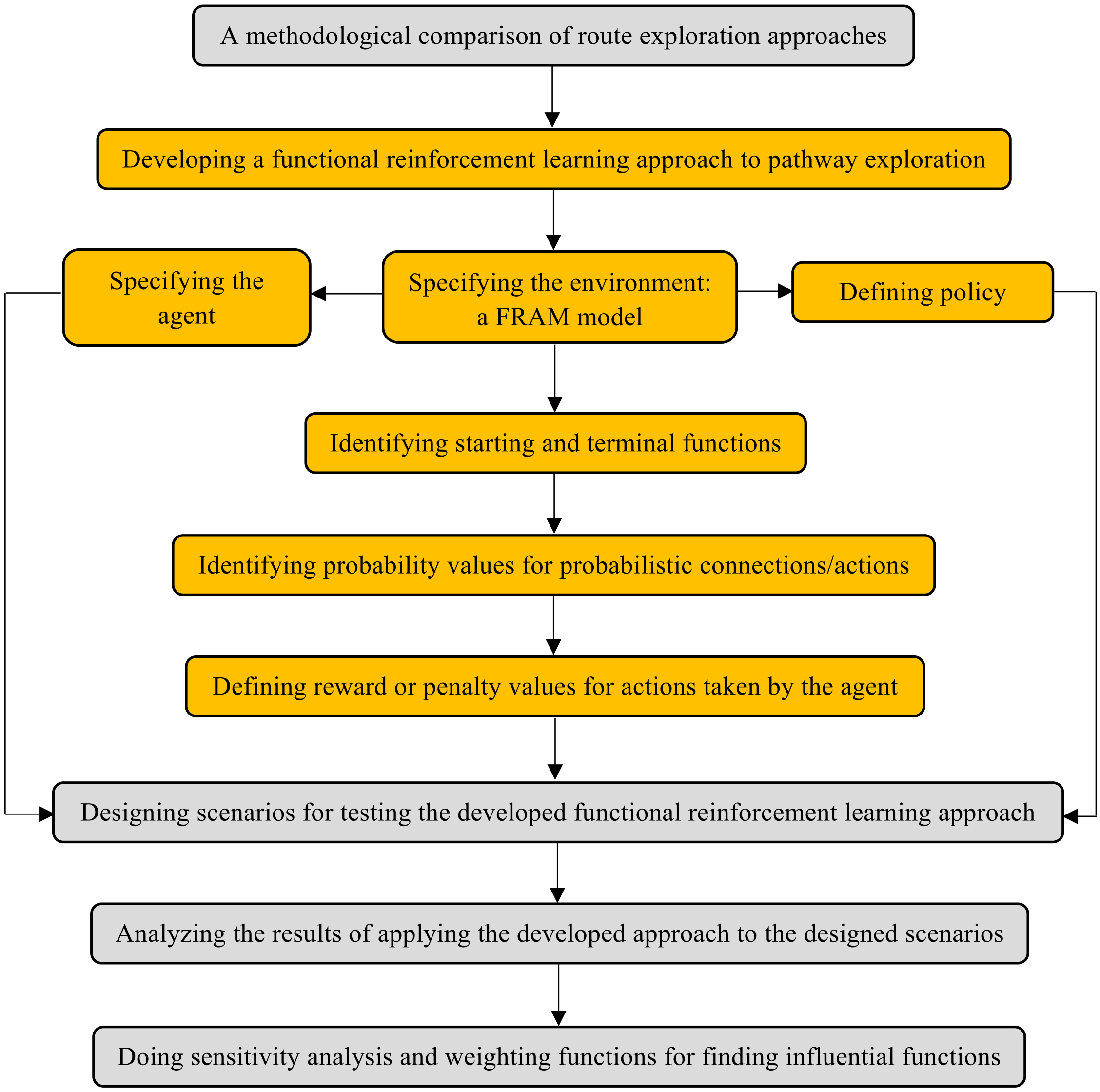

Figure 5.1: The structure of developing and applying the functional RL approach.

5.2.1. Functional modelling using the FRAM

The FRAM is a systems thinking approach that focuses on modelling the entire system rather than concentrating on separate activities or on individual elements (Hollnagel, 2012b). A collection of functions or activities and their connections/couplings constitute a FRAM model. Functions are executed to help a system achieve its final goal. Each function is described by six aspects, including input, output, resources, control, preconditions, and time (Hollnagel, 2012b). The function is represented as a hexagon in FRAM models. Figure 5.2 shows a function with a brief description of the six aspects.

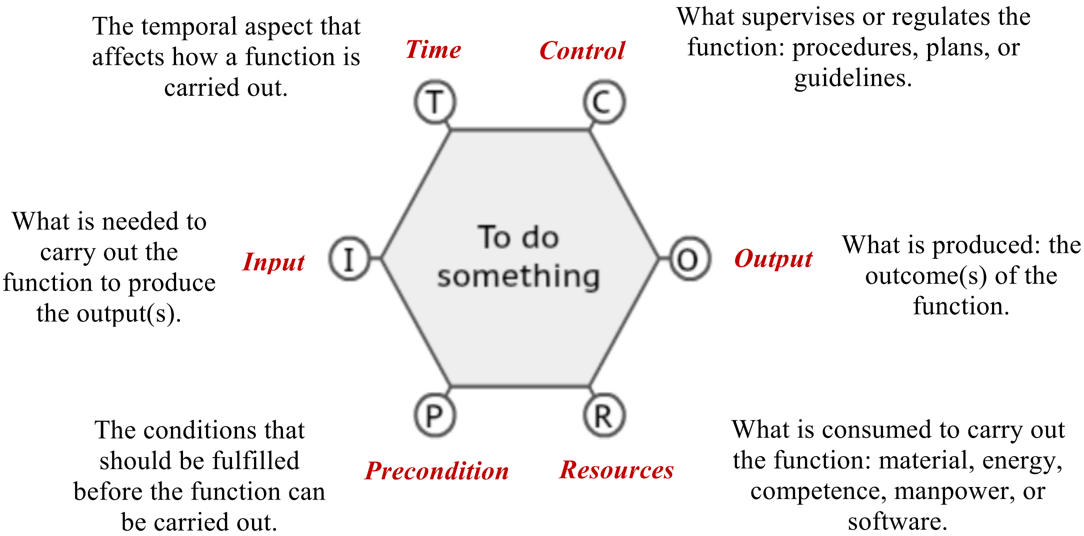

Figure 5.2: A brief description of the aspects of a function (Hollnagel, 2012).

Function identification is the basic step of building a FRAM model (Hollnagel, 2012b). The idea is to identify as many functions as possible (Hollnagel, 2012b). Interviewing the people who perform daily activities (work-as-done) and the experts who prescribe procedures (work-as-imagined) is a well-known approach to identifying functions (Hollnagel, 2012; Salehi, Veitch, et al., 2021). Another source for function identification is to review relevant documents that describe the functionality of a system or a subsystem (Kaya et al., 2021; Salehi, Hanson, et al., 2021). There are other sources for identifying functions, such focus group meetings and workshops (Patriarca et al., 2020; Salehi, Veitch, et al., 2021). After function identification, each function should be described by its aspects. The next step is to link functions. The link between two functions is called coupling, interaction, connection, or dependency. The input of each function can be linked to the output(s) of upstream function(s), and the output(s) of a function can be linked to any aspects of downstream functions other than the output (Hollnagel, 2012b). Specifying the aspects of functions (particularly the output(s) of functions) can help find functional interactions and facilitate building a FRAM model (Salehi, Smith, et al., 2021). The model represents most of the ways that the system can function and achieve its goal. During a specific period of time, the system may use only some of the functions to achieve its goal. A set of functions carried out by the system constitute a functional pathway. If a functional pathway produces functional outputs and an outcome for the entire system in a specific period of time, it can be called an instantiation (del Carmen Pardo-Ferreira et al., 2020; Salehi, Smith, et al., 2021) or a functional signature (Doug Smith et al., 2020). A FRAM model can include different functional pathways, instantiations, or functional signatures (del Carmen Pardo-Ferreira et al., 2020).

5.2.2. Reinforcement learning (RL)

RL is a machine learning technique and aims to learn a task by interacting with an environment (Aboutorab et al., 2022). It requires an environment, agent, state, action, and reward or penalty. An agent finds the current state/function of the environment and chooses the best possible action in each scenario to reach its objective. The agent receives a reward or a penalty based on the action taken. It uses this approach to improve the next action in the next state of the environment. The agent learns and strives to accomplish its objective in the best possible way based on a trial-error approach (Sutton & Barto, 2018).

Pathway exploration related problems can be formulated by Markov Decision Processes (MDPs). A finite set of states (S), another finite set of actions (A), a matrix of state probabilities (P), a reward signal (R), and a discount factor (γ) are required to shape an MDP. The result of solving the MDP provides an optimal policy including the best action that must be taken at a specific state (Sutton & Barto, 2018).

A basic algorithm for addressing RL related problems is Q-learning, which was introduced by Watkins & Dayan (1992). The basis of the Q-learning algorithm is the action value function Q(s,a), which is shown in Equation 1.

$$Q(s,a) \leftarrow Q(s,a) + \alpha[r + \gamma\, max_{a'} Q(s',a') - Q(s,a)] \qquad (1)$$

where: s *and* a are the current state and action, respectively,

s' *and* a' are the next state and action, respectively,

α is the learning rate,

r is the reward value,

γ is the discount factor.

5.3. Developing the functional reinforcement learning approach

In this study, we aim to develop a functional reinforcement learning approach including an artificial agent that learns from its interactions with an environment and explores functional pathways that have the potential to affect the operations in complex socio-technical systems (Figure 5.3). Exploring functional pathways is of great importance as some of the pathways have the potential to negatively or positively influence the system's performance. There are different types of RL algorithms, and researchers choose an algorithm based on the conditions of the problem, including objective(s), possible states, and possible actions. The developed approach of this study employs the Q-learning algorithm as it suits a situation where the number of states and actions is limited.

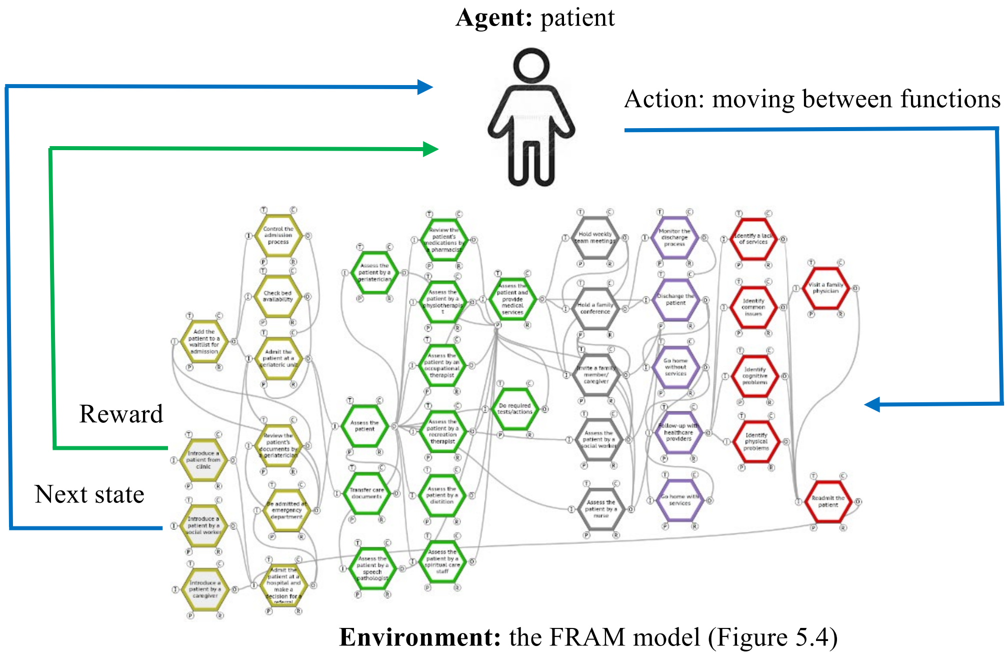

Figure 5.3: The functional reinforcement learning approach of this study.

5.3.1. Initial requirements

A functional reinforcement learning approach requires consideration of an environment, an agent, a set of states, a policy, and rewards that are described in this section.

5.3.1.1. A FRAM model for representing the functional environment

As described in the structure of this study (Figure 5.1), the environment should be specified for the artificial agent to move and act in. Here, a FRAM model of a healthcare operation is considered the environment where the agent can act and move from one function to another (Figure 5.4). Healthcare operations are complex as they consist of various interactions among different system elements, including technology, human, and organization (Dekker, 2012). As shown in Figure 5.4, the FRAM model describes the operations associated with the transition processes of frail older adults from hospital to home in terms of functions. The FRAM model was originally generated by Salehi, Hanson, et al. (2021) based on the data gathered by interviewing healthcare providers and patients/caregivers, observing patients' conditions, and reviewing patients' health records. The current study uses the FRAM model as the environment to examine the developed functional RL approach. The data from Salehi, Hanson, et al. (2021) are also used for secondary analyses, particularly for calculating the set of probabilities for possibilistic connections.

A full list of the functions constituting the FRAM model is presented in Table 5.3. As shown in the table, a unique code is assigned to each function. The code assigned to each function is used to show the state of the agent in the environment. The functional environment/model using the assigned codes is presented in Figure 5.5.

Table 5.3: The information related to the functions used in this study.

Function code	Function name
f_0	Hold a family conference
f_1	Assess the patient by a physiotherapist
f_2	Assess the patient by a nurse
f_3	Go home without services
f_4	Discharge the patient
f_5	Review the patient's documents by a geriatrician
f_6	Admit the patient at a hospital and make a decision for a referral
f_7	Add the patient to a waitlist for admission
f_8	Admit the patient at a geriatric unit
f_9	Hold weekly team meetings
f_{10}	Monitor the discharge process
f_{11}	Assess the patient by a social worker
f_{12}	Introduce a patient from clinic
f_{13}	Introduce a patient by a social worker
f_{14}	Follow-up with healthcare providers
f_{15}	Go home with services
f_{16}	Readmit the patient
f_{17}	Identify cognitive problems
f_{18}	Identify physical problems
f_{19}	Identify common issues
f_{20}	Identify a lack of services
f_{21}	Assess the patient by an occupational therapist
f_{22}	Assess the patient
f_{23}	Assess the patient by a recreation therapist
f_{24}	Assess the patient by a dietitian
f_{25}	Introduce a patient by a caregiver
f_{26}	Invite a family member/caregiver
f_{27}	Visit a family physician
f_{28}	Assess the patient by a geriatrician
f_{29}	Review the patient's medications by a pharmacist
f_{30}	Assess the patient by a speech pathologist
f_{31}	Assess the patient by a spiritual care staff
f_{32}	Transfer care documents
f_{33}	Control the admission process
f_{34}	Check bed availability
f_{35}	Assess the patient and provide medical services
f_{36}	Be admitted at emergency department
f_{37}	Do required tests/actions

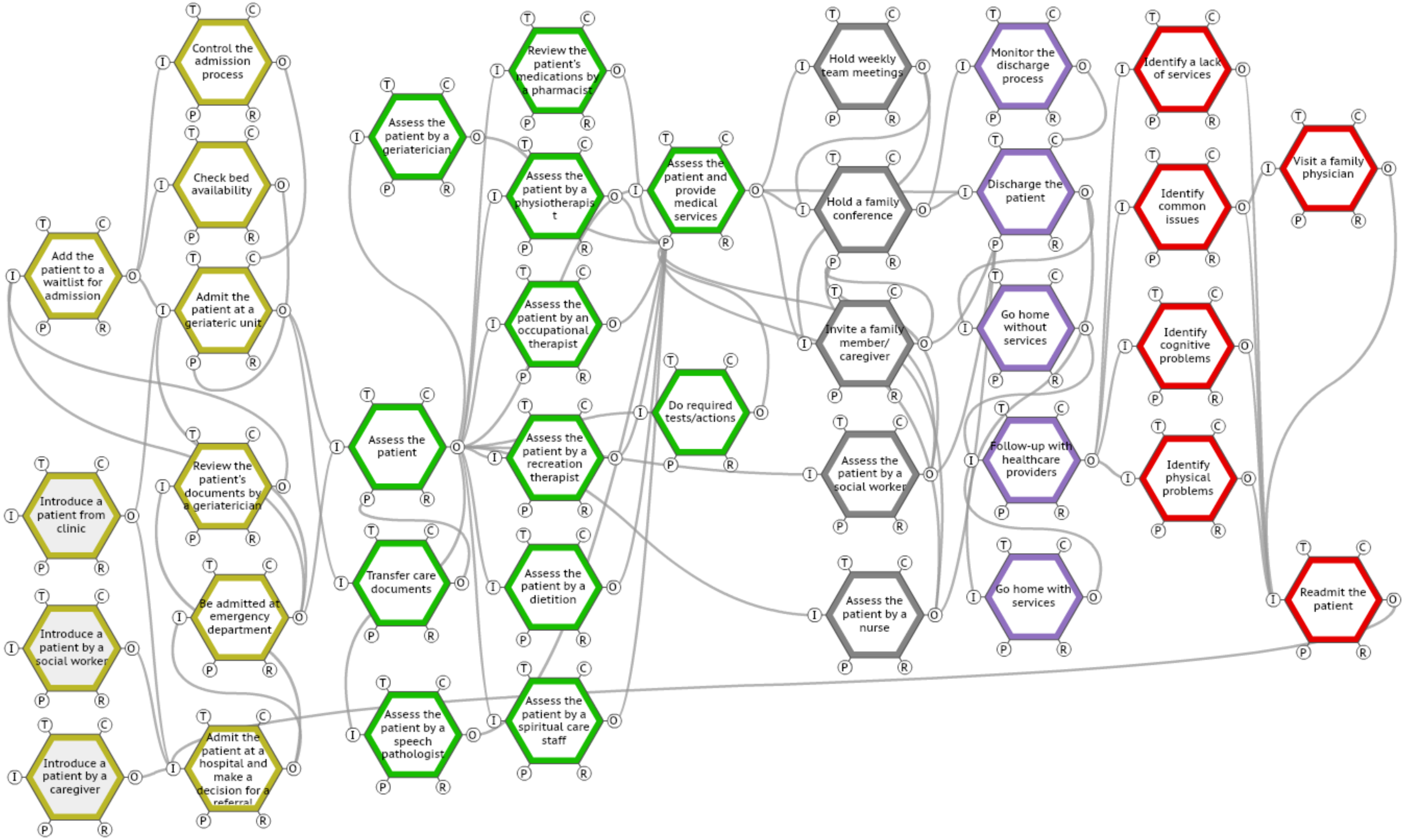

Figure 5.4: A FRAM model of the transition process of older adults (Salehi, Hanson, et al., 2021).

5.3.1.2. Other requirements

- **Agent:** An artificial agent is considered to explore the functional environment. It performs the role of a patient in the healthcare operation.
- **State:** Each state is shown by the location of the function in the functional environment. In other words, each state is represented by a function. The current state is represented by the current function, and the next step is shown by the downstream function.
- **Action:** The functional environment includes 38 functions. The agent can move between the functions and take an action based on the quality of functional outputs, which is reflected in the values of probability and reward.
- **Policy:** It guides the agent/patient on how to act in a situation. The policy of this study is to maximize the quality of functional outputs for the agent/patient during the transition process.
- **Reward values:** Rewards are defined to incentivize the agent to reach its goal and to maximize the effectiveness of the agent. The value of the reward shows how good or bad the action is.

5.3.2. Implementing functional reinforcement learning in healthcare operations

5.3.2.1. Starting and terminal points

The journey of the agent should start from one function and end in another function.

- **Starting functions:** Three functions constitute the starting functions of this study. The agent could start its journey from one of these three functions: f_{12} (Introduce a patient from clinic), f_{13} (Introduce a patient by a social worker), or f_{25} (Introduce a patient by a caregiver). They are shown in grey color in Figure 5.5.
- **Terminal functions:** The agent should be able to finish its journey. The following functions help the agent finish its journey: f_3 (Go home without services), f_{15} (Go home with services), or f_{16} (Readmit the patient). Terminal functions are shown in orange color in Figure 5.5.

5.3.2.2. The policy

The policy is used to guide the agent to take an action in each state. The agent should take an action based on the quality of functional outputs in each state. The actions should be taken within the functional environment generated by FRAM. In other words, the set of actions is limited to the connections between functions (functional connections). The agent decides how to move from the current state (function) to the next state (downstream function) based on the quality of functional outputs that is determined by the values of probability and reward assigned to each function. The aim is to help the agent act based on an optimal policy in its exploration.

5.3.2.3. Deterministic and probabilistic connections

The connections (or couplings) of the functional environment (FRAM model) could be either deterministic or probabilistic. Likewise, the actions taken by the agent are considered either deterministic or probabilistic.

- **Deterministic connections:** Functions could have a single connection. In other words, there is only one possibility to connect the current function to the downstream function. When there is just one connection between the current function and the downstream function, the connection is called deterministic. For instance, the connection between Function 13 (f_{13}) and Function 6 (f_6) is a deterministic connection as there is only one possibility to connect f_{13} to other functions (Figure 5.5).
- **Probabilistic connections:** Some functions have multiple connections. In such conditions, there are multiple possibilities to connect the current function to downstream functions. When there is more than one connection between the current function and downstream functions, the connections are called probabilistic. As shown in Figure 5.5, there are two possible ways to connect f_6 to the next two functions: 1) f_6 to f_5 and 2) f_6 to f_{36}. These connections are called probabilistic connections as the agent should choose only one of these two possible ways to move to the next state (downstream function).

A set of probabilities associated with the possibilistic connections is required to help the agent take the best action. This study used the basic formula of calculating probability presented in Equation 2 to calculate the probability of probabilistic connections.

$$P(E) = \frac{n(E)}{n(S)} \qquad (2)$$

where P(E) is the probability of an event "E", n(E) is the number of favorable outcomes, and n(S) is the total number of events in the sample space (S. M. Ross, 2014).

The probabilities of the probabilistic connections were calculated based on data availability related to six patients/caregivers and two healthcare providers presented in the study published by Salehi, Hanson, et al. (2021). The probabilities of all functional connections within the FRAM model are calculated and presented in both Figure 5.5 and Table 5.4. For instance, the probabilities of occurring ($f_6 \rightarrow f_5$) and ($f_6 \rightarrow f_{36}$) are calculated as follows:

$$P(f_6 \rightarrow f_5) = \frac{4}{6} = 0.67, and\ P(f_6 \rightarrow f_{36}) = \frac{2}{6} = 0.33.$$

This means that four (out of six) patients selected f_5 as downstream function and two (out of six) patients selected f_{36} as the downstream function in their experience (work-as-done).

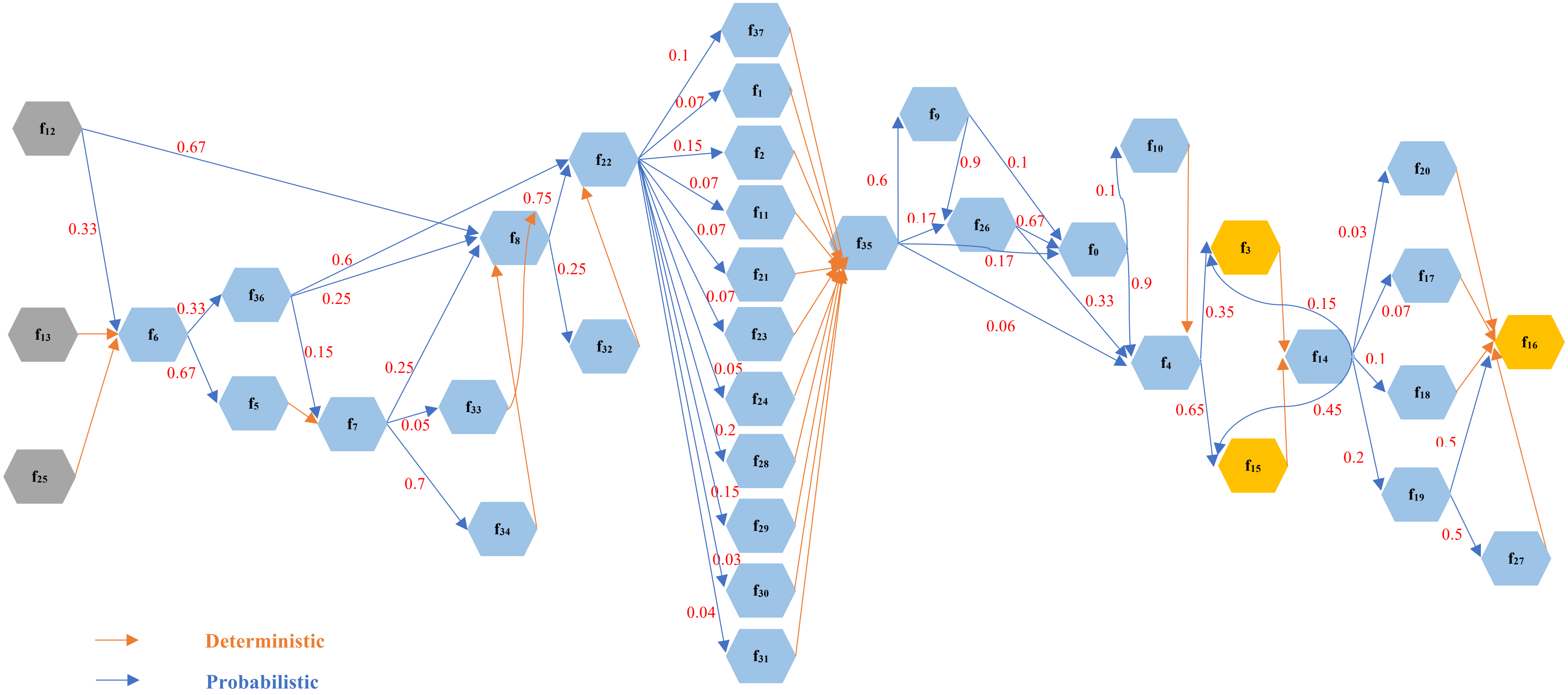

Figure 5.5: Deterministic and probabilistic connections of the functional environment. The probabilities of the probabilistic connections are shown on the connections.

5.3.2.4. Reward values

In this study, reward values are defined to incentivize the agent to take the best actions to reach its objective during the journey. Two types of reward are considered: immediate reward and long-term reward. After taking an action, the agent receives an immediate reward. The quality of care and services the patient/agent receives after executing a function is reflected in the immediate reward value. The quality of functional outputs is classified in three categories: unacceptable, acceptable, and good. The long-term reward accumulates all expected future rewards that the agent receives from the current state/function to the terminal point/function. Both immediate rewards and long-term rewards are necessary in the analyses related to using the functional RL approach in this study. The reward value assigned to each action was assumed by the research team of this study based on the contribution of the action to improvements in the well-being of patients and the overall effectiveness of a hospital to home transition. The reward values assigned to the possible actions taken by the agent are shown in Table 5.4.

Table 5.4: Probability and reward values assigned to the possible actions taken by the agent.

Current state	Next state	Probability	Reward (good, acceptable, unacceptable)	Current state	Next state	Probability	Reward (good, acceptable, unacceptable)
f_{12}	f_8	0.67	(20, 10, -20)	f_{24}	f_{35}	1	(10, 5, -10)
f_{12}	f_6	0.33	(1, 0.5, -1)	f_{22}	f_{31}	0.04	(1, 0.5, -1)
f_{13}	f_6	1	(1, 0.5, -1)	f_{31}	f_{35}	1	(10, 5, -10)
f_{25}	f_6	1	(1, 0.5, -1)	f_{22}	f_{30}	0.03	(2, 1, -2)
f_6	f_{36}	0.33	(1, 0.5, -1)	f_{30}	f_{35}	1	(10, 5, -10)
f_6	f_5	0.67	(5, 2.5, -5)	f_{35}	f_9	0.6	(3, 1.5, -3)
f_{36}	f_{22}	0.6	(10, 5, -10)	f_{35}	f_{26}	0.17	(1, 0.5, -1)
f_{36}	f_8	0.25	(5, 2.5, -5)	f_{35}	f_0	0.17	(5, 2.5, -5)
f_{36}	f_7	0.15	(1, 0.5, -1)	f_{35}	f_4	0.06	(-1, -1, -10)
f_5	f_7	1	(1, 0.5, -1)	f_9	f_0	0.1	(1, 0.5, -1)
f_7	f_8	0.25	(5, 2.5, -5)	f_9	f_{26}	0.9	(2, 1, -2)
f_7	f_{33}	0.05	(1, 0.5, -1)	f_{26}	f_0	0.67	(3, 1.5, -3)
f_7	f_{34}	0.7	(2, 1, -2)	f_{26}	f_4	0.33	(1, 0.5, -1)
f_{33}	f_8	1	(1, 0.5, -1)	f_0	f_{10}	0.1	(1, 0.5, -1)
f_{34}	f_8	1	(1, 0.5, -1)	f_0	f_4	0.9	(5, 2.5, -5)
f_8	f_{22}	0.75	(5, 2.5, -5)	f_{10}	f_4	1	(3, 1.5, -3)
f_8	f_{32}	0.25	(1, 0.5, -1)	f_4	f_3	0.65	(1, 0.5, -1)
f_{32}	f_{22}	1	(1, 0.5, -1)	f_4	f_{15}	0.35	(5, 2.5, -5)
f_{22}	f_{28}	0.2	(10, 5, -10)	f_3	f_{14}	1	(5, 2.5, -5)
f_{28}	f_{35}	1	(10, 5, -10)	f_{15}	f_{14}	1	(5, 2.5, -5)
f_{22}	f_{29}	0.15	(8, 4, -8)	f_{14}	f_{15}	0.45	(10, 5, -10)
f_{29}	f_{35}	1	(10, 5, -10)	f_{14}	f_3	0.15	(10, 5, -10)
f_{22}	f_2	0.15	(7, 3.5, -7)	f_{14}	f_{20}	0.03	(10, 5, -10)
f_2	f_{35}	1	(10, 5, -10)	f_{14}	f_{17}	0.07	(10, 5, -10)
f_{22}	f_{37}	0.1	(6, 3, -6)	f_{14}	f_{18}	0.1	(10, 5, -10)
f_{37}	f_{35}	1	(10, 5, -10)	f_{14}	f_{19}	0.2	(10, 5, -10)
f_{22}	f_1	0.07	(4, 2, -4)	f_{15}	f_{15}	-	Terminal
f_1	f_{35}	1	(10, 5, -10)	f_3	f_3	-	Terminal
f_{22}	f_{11}	0.07	(6, 3, -6)	f_{20}	f_{16}	1	(3, 1.5, -3)
f_{11}	f_{35}	1	(10, 5, -10)	f_{17}	f_{16}	1	(3, 1.5, -3)
f_{22}	f_{21}	0.07	(4, 2, -4)	f_{18}	f_{16}	1	(3, 1.5, -3)
f_{21}	f_{35}	1	(10, 5, -10)	f_{19}	f_{16}	0.5	(3, 1.5, -3)
f_{22}	f_{23}	0.07	(2, 1, -2)	f_{19}	f_{27}	0.5	(5, 2.5, -5)
f_{23}	f_{35}	1	(10, 5, -10)	f_{27}	f_{16}	1	(3, 1.5, -3)
f_{22}	f_{24}	0.05	(3, 1.5, -3)	f_{16}	f_{16}	-	Terminal

5.4. Designing scenarios

This study considered eight scenarios to test the developed functional RL approach based on the functional state, and where the agent starts and ends its journey. The states that constitute the eight scenarios of this study are shown in Figure 5.6. As there are three starting functions (f_{12}, f_{13}, and f_{25}) and two types of terminal functions ((f_3 or f_{15}) and f_{16}), there are a total of six different testing scenarios (3×2=6). These scenarios are called normal scenarios. This study considers another scenario type, which is called emergency scenario. The emergency scenario is related to the situation where the agent starts its journey from an emergency department (f_{36}). As there are two situations for ending the journey ((f_3 or f_{15}) and f_{16}), there are a total of two emergency scenarios (1×2=2). The information regarding the eight scenarios designed by this study is presented in Table 5.5. The data related to Scenario 3 is shown in Table 5.6.

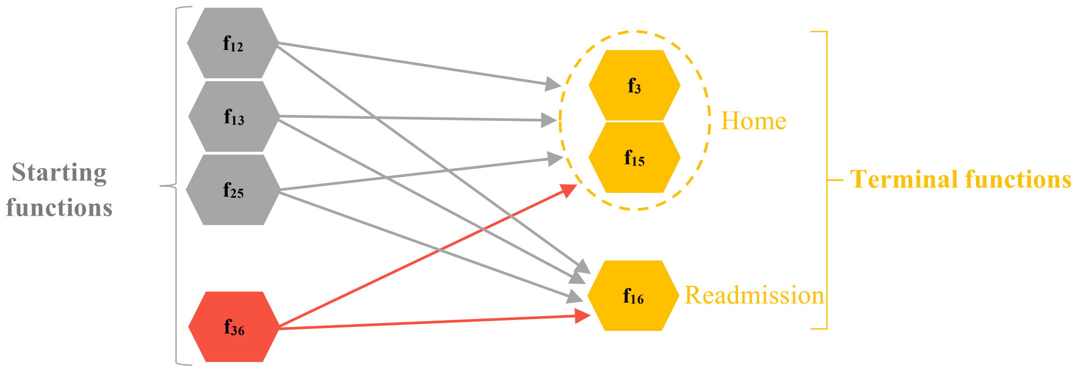

Figure 5.6: The states that constitute the eight scenarios of this study.

Table 5.5: The information related to the scenarios designed in this study.

Scenario no.	Scenario type	Starting function	Terminal function
Scenario 1	Normal	f_{25}	f_{16}
Scenario 2	Normal	f_{13}	f_{16}
Scenario 3	Normal	f_{12}	f_{16}
Scenario 4	Emergency	f_{36}	f_{16}
Scenario 5	Normal	f_{25}	f_3 or f_{15}
Scenario 6	Normal	f_{13}	f_3 or f_{15}
Scenario 7	Normal	f_{12}	f_3 or f_{15}
Scenario 8	Emergency	f_{36}	f_3 or f_{15}

Table 5.6: Scenario 3.

Current state	Next state	Probability	Reward	Current state	Next state	Probability	Reward
f_{12}	f_8	0.67	20	f_{22}	f_{31}	0.04	-1
f_{12}	f_6	0.33	0.5	f_{31}	f_{35}	1	10
f_6	f_{36}	0.33	1	f_{22}	f_{30}	0.03	2
f_6	f_5	0.67	5	f_{30}	f_{35}	1	5
f_{36}	f_{22}	0.6	5	f_{35}	f_9	0.6	3
f_{36}	f_8	0.25	5	f_{35}	f_{26}	0.17	0.5
f_{36}	f_7	0.15	0.5	f_{35}	f_0	0.17	-5
f_5	f_7	1	0.5	f_{35}	f_4	0.06	-1
f_7	f_8	0.25	-5	f_9	f_0	0.1	0.5
f_7	f_{33}	0.05	0.5	f_9	f_{26}	0.9	2
f_7	f_{34}	0.7	2	f_{26}	f_0	0.67	3
f_{33}	f_8	1	-1	f_{26}	f_4	0.33	1
f_{34}	f_8	1	0.5	f_0	f_{10}	0.1	0.5
f_8	f_{22}	0.75	2.5	f_0	f_4	0.9	2.5
f_8	f_{32}	0.25	1	f_{10}	f_4	1	1.5
f_{32}	f_{22}	1	1	f_4	f_3	0.65	1
f_{22}	f_{28}	0.2	5	f_4	f_{15}	0.35	2.5
f_{28}	f_{35}	1	10	f_3	f_{14}	1	2.5
f_{22}	f_{29}	0.15	4	f_{15}	f_{14}	1	-5
f_{29}	f_{35}	1	5	f_{14}	f_{15}	0.45	5
f_{22}	f_2	0.15	7	f_{14}	f_3	0.15	10
f_2	f_{35}	1	5	f_{14}	f_{20}	0.03	10
f_{22}	f_{37}	0.1	6	f_{14}	f_{17}	0.07	10
f_{37}	f_{35}	1	-10	f_{14}	f_{18}	0.1	5
f_{22}	f_1	0.07	-4	f_{14}	f_{19}	0.2	5
f_1	f_{35}	1	10	f_{15}	f_{15}	1	0
f_{22}	f_{11}	0.07	3	f_3	f_3	1	0
f_{11}	f_{35}	1	10	f_{20}	f_{16}	1	1.5
f_{22}	f_{21}	0.07	2	f_{17}	f_{16}	1	3
f_{21}	f_{35}	1	-10	f_{18}	f_{16}	1	-3

f_{22}	f_{23}	0.07	1	f_{19}	f_{16}	0.5	1.5
f_{23}	f_{35}	1	10	f_{19}	f_{27}	0.5	-5
f_{22}	f_{24}	0.05	1.5	f_{27}	f_{16}	1	3
f_{24}	f_{35}	1	-10	f_{16}	f_{16}	1	0

5.5. Results and discussion

5.5.1. Examining the functionality of the developed approach using the designed scenarios

The current study used the eight designed scenarios to examine the functionality of the functional RL approach for assessing the performance of the system through exploring functional pathways in a healthcare operation. The results of applying the functional RL approach to the designed scenarios are presented in Table 5.7. Applying the developed approach to each scenario resulted in identifying a functional pathway and an associated accumulated action value. The accumulated action value is calculated using Equation 1. According to the equation, the action value includes the probability of each action (executing a function) and the reward value related to that action (the quality of care and services after executing a function is reflected in the reward value). Hence, the accumulated action value is considered a judging criterion to assess the performance of the functional pathways regarding the designed scenarios.

The developed functional RL approach is able to identify the functional pathways the agent has taken in terms of the number of functions. In other words, it specifies what functions are involved in the functional pathway related to each scenario that the agent takes during its journey. According to the results shown in Table 5.7, the number of functions in the pathway that the agent took for each of Scenarios 1 and 2 was 20. Both of these scenarios are normal, rather than emergency. These were the longest pathways of the scenarios examined. When the approach was applied to the two emergency scenarios (Scenarios 4 and 8), the results showed that 14 functions constituted the functional pathways of the two emergency scenarios, and the agent experienced the shortest journey among all eight scenarios (Table 5.7).

In addition to identifying the functions involved in the functional pathways taken by the agent, the developed functional RL is also able to compute the accumulated action value for each scenario after the agent completes its journey. The accumulated action value could be used as a criterion to compare functional pathways in order to identify potential pathways that might have positive or negative influence on the performance of a system. The accumulated action values for the eight scenarios are presented in Table 5.7 and Figure 5.7. As illustrated in Figure 5.7, the first highest accumulated action value was recorded for Scenario 3 (accumulated action value = 68.58). The functional pathway related to Scenario 3 is shown in Figure 5.8. The second highest accumulated action value was related to Scenario 7 with an accumulated action value of 62.88. In Scenario 7, the agent took the first action from f_{12} and finished its journey in f_{15} (Table 5.7). In both scenarios, the agent started its journey from f_{12}, but it ended its journey in f_{16} and f_{15} for Scenarios 3 and 7, respectively. According to Figure 5.7, the agent received an equal accumulated action value for both Scenarios 1 and 2. In these two scenarios, the agent started its journey from different functions but ended in same function (f_{16}) (Table 5.7). The lowest accumulated action value was recorded for Scenario 8, where the functional pathway between the starting function (f_{36}) and the terminal function (f_3) was the shortest.

Table 5.7: The results of applying the developed functional RL approach to the scenarios.

Scenarios	**Functions involved in the functional pathway taken by the agent**	**Accumulated action value**
Scenario 1	f_{25}, f_6, f_5, f_7, f_8, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_9, f_{26}, f_0, f_4, f_{15}, f_{14}, f_{19}, f_{27}, f_{16}	58.02
Scenario 2	f_{13}, f_6, f_5, f_7, f_8, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_9, f_{26}, f_0, f_4, f_{15}, f_{14}, f_{19}, f_{27}, f_{16}	58.02
Scenario 3	f_{12}, f_8, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_9, f_{26}, f_0, f_4, f_{15}, f_{14}, f_{19}, f_{27}, f_{16}	68.58
Scenario 4	f_{36}, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_0, f_4, f_{15}, f_{14}, f_{19}, f_{27}, f_{16}	52.98
Scenario 5	f_{25}, f_6, f_5, f_7, f_8, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_9, f_{26}, f_0, f_4, f_{15}, f_{14}, f_{15}	52.18
Scenario 6	f_{13}, f_6, f_5, f_7, f_8, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_9, f_{26}, f_0, f_4, f_{15}, f_{14}, f_3	52.32
Scenario 7	f_{12}, f_8, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_9, f_{26}, f_0, f_4, f_{15}, f_{14}, f_{15}	62.88
Scenario 8	f_{36}, f_{22}, f_{28}, f_{29}, f_2, f_{37}, f_{35}, f_9, f_{26}, f_0, f_4, f_{15}, f_{14}, f_3	48.63
Average	**-**	**56.70**

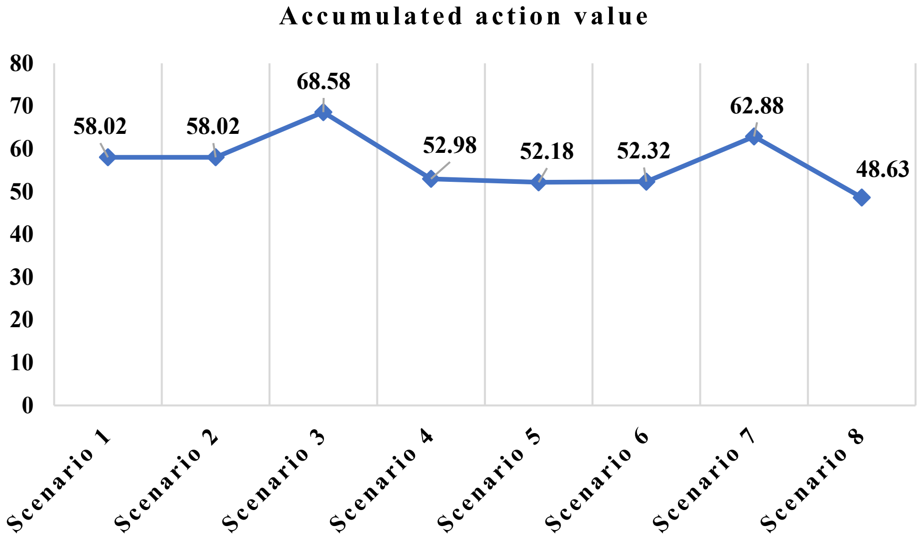

Figure 5.7: Accumulated action values calculated for the scenarios of this study.

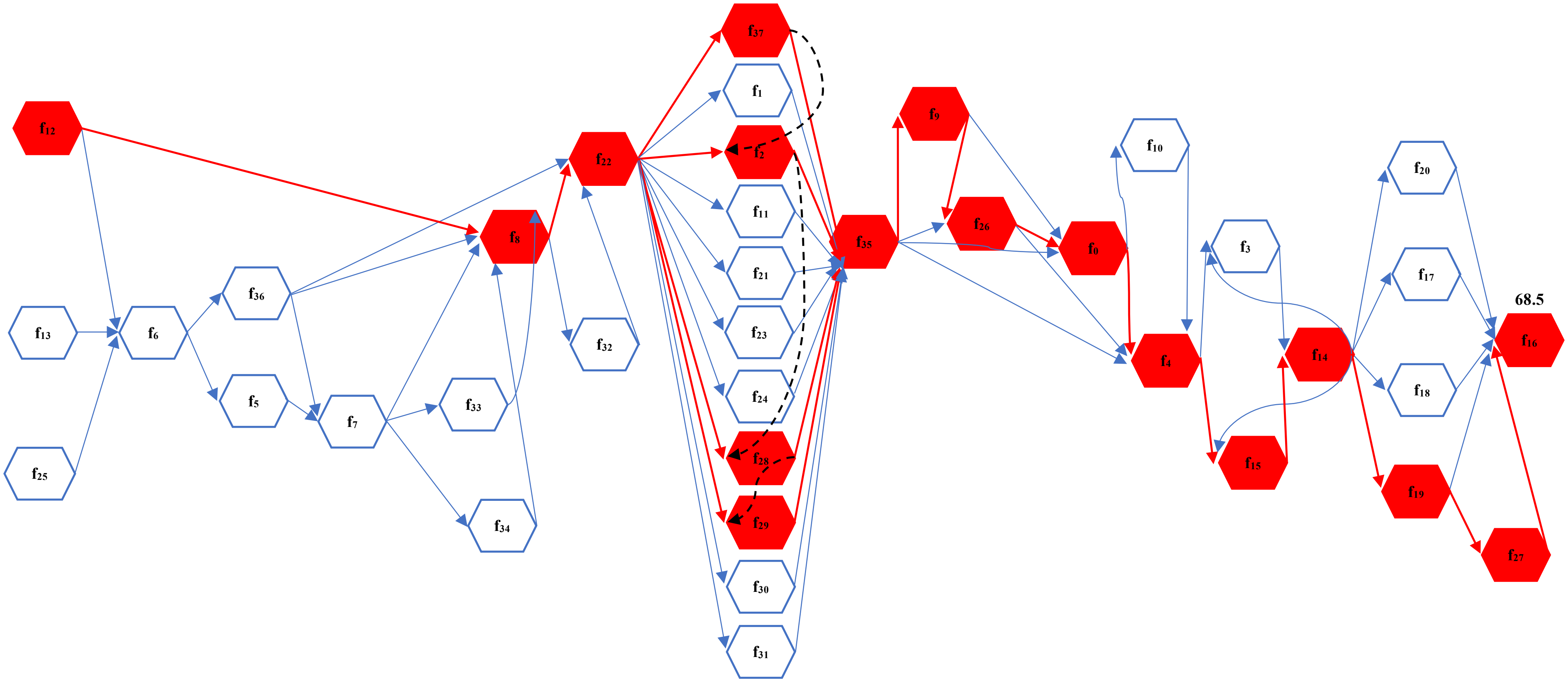

Figure 5.8: The functional pathway with the highest accumulated action value is related to Scenario 3.

5.5.2. Sensitivity analysis

In this study, sensitivity analysis is performed to reveal the ability of the functional RL approach to identify the relative importance of functions and their influence on the system performance in a healthcare operation. To demonstrate this ability, this study attempts to find the importance of the four functions that might affect the discharge process (f_4). The four functions are f_{26} (invite a caregiver), f_0 (hold a family conference), f_{10} (monitor the discharge process), and f_9 (hold team meetings). To this end, the developed approach was run four times for the eight scenarios. It is worth mentioning that one function should be eliminated in each run, and the accumulated action value is calculated. Then the discrepancy between the accumulated action values before and after function elimination is computed. The highest discrepancy indicates the highest importance. The initial results associated with the sensitivity analysis are presented in Table 5.8.

According to Table 5.8, the second column shows the accumulated action value for each scenario in the presence of all functions before function elimination. The accumulated action values related to all eight scenarios are presented in the third column when f_{26} (invite a caregiver) is eliminated from the list of functions and the results are computed based on the remaining functions. The results pertaining to other functions were similarly calculated and are provided in the table. Table 5.8 also shows the average of the accumulated action values after the elimination of each function. For instance, the average of the accumulated action values when omitting f_{26} (invite a caregiver) equals 40.11.

The discrepancy between the average of the accumulated action values before and after function elimination was computed for the four functions in order to determine the importance of each function for the discharge process (f_4). The discrepancies are shown in Table 5.9. The results show that the greatest discrepancy is related to the omission of f_0 (hold a family conference) (Table 5.9: 56.70-39.63= 17.07). Hence, this function is the most important function in the improvement of the discharge process (f_4). Likewise, f_{26} (invite a caregiver) and f_9 (hold team meetings) are the second and third significant functions respectively and can be influential on the enhancement of the discharge process (f_4).

Table 5.8: The results of sensitivity analysis considering the accumulated action value.

Scenarios	Accumulated action value before function elimination	Accumulated action value after eliminating f_{26} (invite a caregiver)	Accumulated action value after eliminating f_0 (hold a family conference)	Accumulated action value after eliminating f_{10} (monitor the discharge process)	Accumulated action value after eliminating f_9 (hold team meetings)
Scenario 1	58.02	39.21	38.74	56.39	40.29
Scenario 2	58.02	39.21	38.74	56.03	40.24
Scenario 3	68.58	49.78	49.31	66.95	50.85
Scenario 4	52.98	35.53	35.06	52.70	36.60
Scenario 5	52.18	37.56	37.07	51.08	38.01
Scenario 6	52.32	37.56	37.07	49.01	38.01
Scenario 7	62.88	48.13	47.63	61.66	48.57
Scenario 8	48.63	33.88	33.38	47.41	34.32
Average	**56.70**	**40.11**	**39.63**	**55.15**	**40.86**

Table 5.9: Discrepancy between the average of the accumulated action values before and after function elimination.

Eliminated function	f_{26} (invite a caregiver)	f_0 (hold a family conference)	f_{10} (monitor the discharge process)	f_9 (hold team meetings)
The amount of discrepancy	56.70-40.11= **16.59**	56.70-39.63= **17.07**	**1.55**	**15.84**

5.5.3. Computing the weights of the functions

In this section, the weights of the four functions affecting the discharge process are computed based on the results of the sensitivity analysis. These weights are calculated based on the percentage of changes into the accumulated action value mean created by each function (Table 5.9). To this end, the discrepancies for the eliminated functions were calculated and are presented in Table 5.9. Computing weights is performed through Equation (3), where d_i represents the discrepancy related to each eliminated function, and n equals the number of scenarios. According to Equation (3), the weight of each function can be calculated by dividing the amount of discrepancy associated with each eliminated function by the amount of the total discrepancy. The weights of all functions influencing the discharge process are shown in Figure 5.9. As presented in Figure 5.9, f_0 (hold a family conference) with 34% had the highest weight among the four investigated functions, which indicates the importance of this function in the discharge process. The results of the weight calculation also showed that f_{26} (invite a caregiver) and f_9 (hold team meetings) were the second and third most effective functions on the discharge process with 32% and 31%, respectively. Finally, Figure 5.9 indicates f_{10} (monitor the discharge process) with 3% was the least important function.

$$w_i = \frac{d_i}{\sum_{i=1}^{n} d_i} * 100 \qquad (3)$$

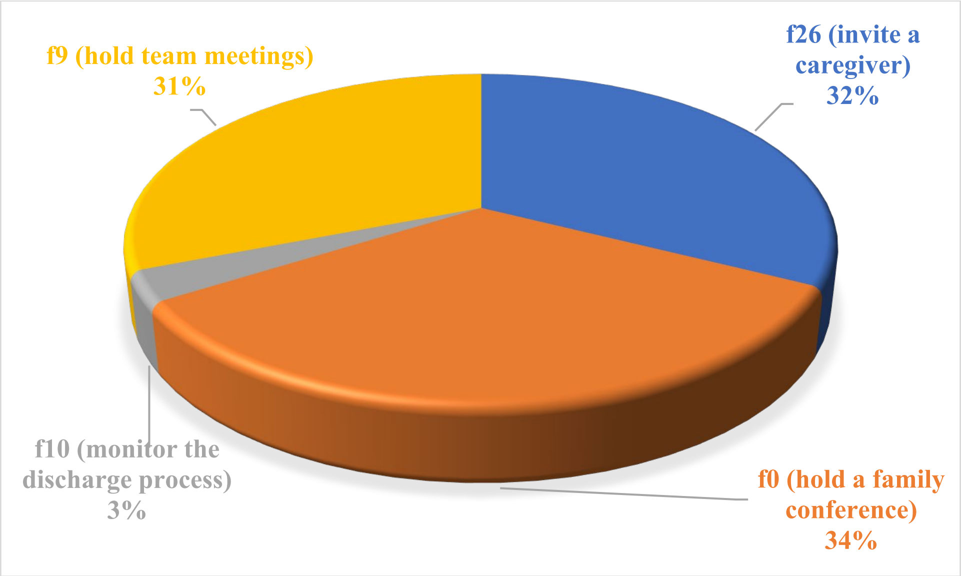

Figure 5.9: The weight of each function.

Reviewing the findings of this study shows that using the RL approach in function-based operations can lead to identifying the potential pathways that might affect the performance of a complex system. An in-depth analysis of functional pathways can result in distinguishing risky and safe functional pathways. This distinction enables system managers to assign resources (human, material, time, and information) to safe pathways in order to improve the system performance. It also helps managers and decision-makers to insert barriers into risky pathways in order to reduce the severity of undesirable outcomes, as highlighted by Adriaensen et al. (2021). It can lead to preventing investment on activities or operations that might have negative effect on the system performance. Analyzing functional pathways generated based on work-as-done can help system designers to design a more stable system and increase its robustness against internal disturbances and external threats, as mentioned by Hwang & Yoon (2020).

The functional RL approach introduced by this study employed an artificial agent to explore the operations within a functional model. This is an advantageous aspect as the approach is less data dependent. In real-world case studies, finding patients who experienced different functional pathways is time-consuming and is not cost-effective. As pointed out by Piera et al. (2019), the usefulness of employing an agent is justified when information is ambiguous, goals are unclear, and operations are unpredictable. The presence of the agent increases the flexibility of the approach so that the system performance can be examined under different management structures, as pointed out by Piera et al. (2019). It enables system managers to test their systems in different conditions reflected in different scenarios in order to identify influential functions/factors on a specific operation as shown by the sensitivity analysis of this study.

5.6. Study limitations and future research directions

The limitations of this study should be mentioned. First, the information regarding the agent was limited. As the agent performed the role of a patient, the characteristics of the patient could be involved to assess the system performance in a more accurate way. For instance, considering the reasons for admission or ailment may influence the actions taken by the agent. Second, the functional RL approach was examined using scenarios encompassing assumed rewards for all functions. This was a reasonable approach to test the method, but it would be worthwhile in future to compile a reward function based on the views of the system's stakeholders, and then assess the system again using these more credible rewards. It would be possible to define a reward function to help the agent to take actions with more independence. Third, this study only considered the rewards to the patient. In practice, there are several dimensions to the system, each with an associated reward/cost structure. These can be in conflict/competition with each other. Hence, there needs to be a treatment of multi-objective decision environment for a more accurate performance assessment of the system. Fourth, our approach does not account for time-related penalties for late actions, or for time-related changes in the agent itself. The focus of future research could be on assigning penalties (or negative rewards) to activities or tasks that are not executed on time. Another limitation is that our study did not consider the variability of functional outputs. The probability of producing each functional output might be different from others. Considering the probabilities of variable functional outputs can help find the optimal pathway, where negative variations are dampened, and positive variations are amplified.

5.7. Conclusions

FRAM is an appropriate approach for modelling complex socio-technical systems by visualizing activities/functions and their interactions in terms of variability. The ability of the FRAM is mostly limited to qualitative analyses. It is unable to compute and compare the influence of various functional pathways on the system performance. This study developed a functional RL approach to pathway exploration in an environment generated by FRAM. The developed approach enables an artificial agent to explore functional environments and to compare the effects of different functional pathways. An application of the developed functional RL approach to healthcare operations for frail older adults' transitions demonstrated that the approach enables an artificial agent to explore different functional pathways and facilitates comparative analyses to identify safe and risky pathways based on the designed scenarios. The reward values embedded in the functional RL approach motivated the agent to pursue an optimal policy during its exploration. Functional representation of reinforcement learning allows comparative analyses of functional pathways where there are numerous scenarios in complex socio-technical systems. Using the functional RL approach could enable system designers to identify priorities regarding reward structures that promote the use of better functional pathways through the system and enable managers to allocate resources to yield better system performance. Most importantly, it provides guidance on how to provide the best care to patients in light of various circumstances. There is still a lot to explore before this approach can be applied with confidence, but the basic method appears to warrant further development.

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References

Aboutorab, H., Hussain, O. K., Saberi, M., & Hussain, F. K. (2022). A reinforcement learning-based framework for disruption risk identification in supply chains. *Future Generation Computer Systems*, *126*, 110–122.

Adriaensen, A., Costantino, F., Di Gravio, G., & Patriarca, R. (n.d.). Teaming with industrial cobots: A socio-technical perspective on safety analysis. *Human Factors and Ergonomics in Manufacturing & Service Industries*.

Alboghobeish, A., & Shirali, G. A. (2021). Integration of Functional Resonance Analysis with Multicriteria Analysis for Sociotechnical Systems Risk Management. *Risk Analysis*.

Coronato, A., Naeem, M., De Pietro, G., & Paragliola, G. (2020). Reinforcement learning for intelligent healthcare applications: A survey. *Artificial Intelligence in Medicine*, *109*, 101964.

Danial, S. N., Smith, D., & Veitch, B. (2021). A Method to Detect Anomalies in Complex Socio-Technical Operations Using Structural Similarity. *Journal of Marine Science and Engineering*, *9*(2), 212.

de Souza, I. T., Rosa, A. C., Evangelista, A. C. J., Tam, V. W. Y., & Haddad, A. (2021). Modelling the work-as-done in the building maintenance using a layered FRAM: A case study on HVAC maintenance. *Journal of Cleaner Production*, *320*, 128895.

Dekker, S. (2012). Complexity, signal detection, and the application of ergonomics: Reflections on a healthcare case study. *Applied Ergonomics*, *43*(3), 468–472.

del Carmen Pardo-Ferreira, M., Rubio-Romero, J. C., Gibb, A., & Calero-Castro, S. (2020). Using functional resonance analysis method to understand construction activities for concrete structures. *Safety Science*, *128*, 104771.

França, J. E. M., Hollnagel, E., dos Santos, I. J. A. L., & Haddad, A. N. (2019). FRAM AHP approach to analyse offshore oil well drilling and construction focused on human factors. *Cognition, Technology & Work*, 1–13.

Goodfellow, I., Bengio, Y., & Courville, A. (2016). *Deep learning*. MIT press.

Hackel, L. M., Mende-Siedlecki, P., & Amodio, D. M. (2020). Reinforcement learning in social interaction: The distinguishing role of trait inference. *Journal of Experimental Social Psychology*, *88*, 103948.

Hegedűs, T., Németh, B., & Gáspár, P. (2019). Graph-based multi-vehicle overtaking strategy for autonomous vehicles. *IFAC-PapersOnLine*, *52*(5), 372–377.

Hirose, T., Sawaragi, T., & Horiguchi, Y. (2016). Safety analysis of aviation flight-deck procedures using systemic accident model. *IFAC-PapersOnLine*, *49*(19), 19–24.

Hollnagel, E. (2012). *FRAM, the functional resonance analysis method: modelling complex socio-technical systems*. Ashgate Publishing, Ltd.

Huang, W., Yin, D., Xu, Y., Zhang, R., & Xu, M. (2021). Using NK Model to quantitatively calculate the variability in Functional Resonance Analysis Method. *Reliability Engineering & System Safety*, 108058.

Hwang, G. H., & Yoon, W. C. (2020). A new approach to requirement development for a common operational picture to support distributed situation awareness. *Safety Science*, *125*, 104569.

Kaptan, M., Sarıalioğlu, S., Uğurlu, Ö., & Wang, J. (2021). The evolution of the HFACS method used in analysis of marine accidents: A review. *International Journal of Industrial Ergonomics*, *86*, 103225.

Kaya, G. K., Ovali, H. F., & Ozturk, F. (2019). Using the functional resonance analysis method on the drug administration process to assess performance variability. *Safety Science*, *118*, 835–840.

Kaya, G. K., Ozturk, F., & Sariguzel, E. E. (2021). System-based risk analysis in a tram operating system: integrating Monte Carlo simulation with the functional resonance analysis method. *Reliability Engineering & System Safety*, 107835.

Kim, Y. C., & Yoon, W. C. (2021). Quantitative representation of the functional resonance analysis method for risk assessment. *Reliability Engineering & System Safety*, *214*, 107745.

Klar, M., Glatt, M., & Aurich, J. C. (2021). An implementation of a reinforcement learning based algorithm for factory concept layout planning. *Manufacturing Letters*.

Li, T.-H., Wang, Z.-S., Lu, W., Zhang, Q., & Li, D.-F. (2021). Electronic health records based reinforcement learning for treatment optimizing. *Information Systems*, 101878.

Li, W., He, M., Sun, Y., & Cao, Q. (2019). A proactive operational risk identification and analysis framework based on the integration of ACAT and FRAM. *Reliability Engineering & System Safety*, *186*, 101–109.

Liang, X., & Meng, X. (2019). An extended FTOPSIS method for freeway route selection in the pre-feasibility study stage. *Physica A: Statistical Mechanics and Its Applications*, *526*, 120871.

Olawoyin, A., & Chen, Y. (2018). Predicting the future with artificial neural network. *Procedia Computer Science*, *140*, 383–392.

Patriarca, R., & Bergström, J. (2017). Modelling complexity in everyday operations: functional resonance in maritime mooring at quay. *Cognition, Technology & Work*, *19*(4), 711–729.

Patriarca, R., Di Gravio, G., & Costantino, F. (2017). A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. *Safety Science*, *91*, 49–60.

Patriarca, R., Di Gravio, G., Woltjer, R., Costantino, F., Praetorius, G., Ferreira, P., & Hollnagel, E. (2020). Framing the FRAM: A literature review on the functional resonance analysis method. *Safety Science*, *129*, 104827.

Piera, M. A., Ramos, J. J., & Muñoz, J. L. (2019). A socio-technical holistic agent based model to assess cockpit supporting tools performance variability. *IFAC-*

PapersOnLine, *52*(11), 122–127.

Ross, S. M. (2014). *Introduction to probability models*. Academic press.

Salehi, V., Veitch, B., & Musharraf, M. (2020). Measuring and improving adaptive capacity in resilient systems by means of an integrated DEA-Machine learning approach. *Applied Ergonomics*, *82*. https://doi.org/10.1016/j.apergo.2019.102975

Salehi, V., Hanson, N., Smith, D., McCloskey, R., Jarrett, P., & Veitch, B. (2021). Modeling and analyzing hospital to home transition processes of frail older adults using the functional resonance analysis method (FRAM). *Applied Ergonomics*, *93*, 103392.

Salehi, V., Smith, D., Veitch, B., & Hanson, N. (2021). A dynamic version of the FRAM for capturing variability in complex operations. *MethodsX*, *8*, 101333.

Salehi, V., Veitch, B., & Smith, D. (2021). Modeling complex socio-technical systems using the FRAM: A literature review. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *31*(1), 118–142.

Slater, D., Hollnagel, E., MacKinnon, R., Sujan, M., Carson-Stevens, A., Ross, A., & Bowie, P. (2021). A Systems Analysis of the COVID-19 Pandemic Response in the United Kingdom–Part 1-The overall Context. *Safety Science*, 105525.

Smith, D., Veitch, B., Khan, F., & Taylor, R. (2020). Integration of Resilience and FRAM for Safety Management. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *6*(2), 4020008.

Song, R., Jang, S., Wang, Y., Hanssens, D. M., & Suh, J. (2021). Reinforcement learning and risk preference in equity linked notes markets. *Journal of Empirical Finance*.

Studic, M., Majumdar, A., Schuster, W., & Ochieng, W. Y. (2017). A systemic modelling of ground handling services using the functional resonance analysis method. *Transportation Research Part C: Emerging Technologies*, *74*, 245–260.

Sutton, R. S., & Barto, A. G. (2018). *Reinforcement learning: An introduction*. MIT press.

Toroody, A. B., Abaei, M. M., & Gholamnia, R. (2016). Conceptual compression discussion on a multi-linear (FTA) and systematic (FRAM) method in an offshore operation's accident modeling. *International Journal of Occupational Safety and Ergonomics*, *22*(4), 532–540.

Watkins, C. J. C. H., & Dayan, P. (1992). Q-learning. *Machine Learning*, *8*(3–4), 279–292.

Yu, M., Quddus, N., Kravaris, C., & Mannan, M. S. (2020). Development of a FRAM-based framework to identify hazards in a complex system. *Journal of Loss Prevention in the Process Industries*, *63*, 103994.

Zhou, Y., Li, B., & Lin, T. R. (2021). Maintenance optimisation of multicomponent systems using hierarchical coordinated reinforcement learning. *Reliability Engineering & System Safety*, 108078.

Zinetullina, A., Yang, M., Khakzad, N., Golman, B., & Li, X. (2021). Quantitative resilience assessment of chemical process systems using functional resonance analysis method and Dynamic Bayesian network. *Reliability Engineering & System Safety*, *205*, 107232.

Chapter 6

Conclusions & Recommendations

6.1. Conclusions

The hospital to home transition process of frail older adults is a complex procedure covering admission, assessment, treatment, discharge, follow up, and readmission of patients. The process links hospital, home, and community to improve patients' health and safety. The transition processes are critical and vulnerable points in the provision of healthcare. Transitions between hospital and home are complex, multiple-step processes that require systemic approaches to understand the complexity among the patient, their caregivers, the healthcare providers, and home and community care providers. This PhD thesis focuses on the application of the FRAM, DynaFRAM, and reinforcement learning to model, analyze, and improve the hospital-to-home transition processes of frail older adults.

The application of the FRAM provides guidance on complexity management in complex socio-technical systems. The FRAM can address the problems of complex socio-technical systems by investigating technological, human, organizational, and other external factors affecting complex systems' boundaries. Despite several advantages for modeling complex systems and safety management, the FRAM has a few deficiencies. There is a clear need for exploring further research opportunities to address the flaws and deficiencies around the FRAM to satisfy the variability-related demands of complex socio-technical systems. The DynaFRAM, a dynamic version of the FRAM, was examined in healthcare operations to address the variability-related deficiencies of the FRAM-related tools. The application of the DynaFRAM to a transition model of frail older adults demonstrated its ability to visualize the functionality of the transition process and to characterize performance variability in the outputs of functions and in the outcomes of the entire system. The application of the DynaFRAM also assists the healthcare system to know where a patient is and what steps they have in front to discharge from hospital. It also allows healthcare providers to know what types of services and medications a patient receives during the transition process.

When the suitability of the FRAM and DynaFRAM has been demonstrated throughout this thesis, healthcare has been the area of application. When building the FRAM model of the transition process, the perspectives of healthcare providers, patients, and caregivers were used to address the complexity of the process. The FRAM helped create a library of 38 functions, including five categories: admission process, patient assessment and treatment, synthesis, decision making, and readmission process. Also, the information regarding patients' experience during the transition process revealed how performance variability related to the outputs of everyday activities results in adversities and challenges for frail patients. However, the ability of the FRAM is mostly limited to qualitative analyses. This PhD research project coupled the FRAM to reinforcement learning to explore functional environments using an artificial agent. An application of the introduced approach to healthcare operations for frail older adults' transitions demonstrated that the approach enables the agent to explore different functional pathways and facilitates comparative analyses to identify safe and risky pathways. Most importantly, it provides guidance on how to provide the best care and services to frail patients during the transition process in the light of various circumstances. There is still a lot to explore before this approach can be applied with confidence, but the basic method appears to warrant further development.

6.2. Limitations, recommendations & future work

This PhD research work investigates the application of the FRAM, DynaFRAM, and reinforcement learning to transition processes of frail older adults. The limitations of this PhD research work are described, and future research works are discussed.

The evolution of the FRAM is important for future research. Building a FRAM model is still time consuming. Developing (semi-) automatic data extraction approaches, including function identification and aspect specification, could be useful in saving time for constructing FRAM models. Approach(es) for quantifying variability should also be developed in terms of (at least) time and precision. Different attempts have not resulted in a formal quantitative approach for calculating variability yet, although research interest has grown in this regard, as exemplified by the use of fuzzy logic (Hirose & Sawaragi, 2020) and the concept of functional signatures (Smith et al., 2020). The ability of the DynaFRAM tool was assessed to capture different characteristics of variability in healthcare operations considering limited information. The information used in this research was limited to just six patients, although in-depth data were gathered for each patient. Data collection process in healthcare systems is a big challenge particularly in the time of the COVID-19 pandemic. A bigger sample size could be a better and more accurate basis for evaluating the capability of the DynaFRAM tool in capturing variability. To this end, future studies will take a supplementary step of collecting further patient data to expand the scope of this research. Future research could concentrate on performance variability of functions' outputs. This, in turn, allows researchers to calculate the aggregation of variability and to recommend appropriate policies to manage variability in daily operations of the transition process so that frail patients improve the safety and quality of their lives. In the meantime, the generalizability of the results will be reinforced due to more diversity and number of frail patients.

As exposed in the time of the COVID-19 pandemic, the efficiency of healthcare systems is low, and costs are high. Future research could also focus on the formulation and development of public health policies for frail older people during hospital to home transitions, which may affect the performance of the healthcare system. Moreover, trade-offs between efficiency and thoroughness, known as the ETTO principle, could be investigated in the future. Requirements, including resources, should be met to achieve acceptable performance to ensure system operation (Hollnagel, 2009). The focus will be on researching the trade-off between acceptable (or unacceptable) performance and meeting requirements and current conditions. Investigating differences between work-as-done and work-as-imagined has a great potential for future research. The possible gap between protocols and procedures of the transition process (work-as-imagined) and observations of patients' transitions (work-as-done) will be a basis to improve the quality of care during the transition process for frail patients.

The FRAM was combined with reinforcement learning to create a basis for defining the environment that is explored by an artificial agent to assess functional pathways. The information regarding the artificial agent who explored the functional environment based on reinforcement learning principles was also limited. As the agent performed the role of a patient, the characteristics of the patient could be involved to assess the transitional pathways in a more accurate way. For instance, considering the reasons for admission or ailment may influence the actions taken by the agent. This should be considered in future research work as there is an element of randomness in the actual system. The functional reinforcement learning approach was examined using scenarios encompassing assumed rewards for all functions. This was a reasonable approach to test the method, but it would be worthwhile in future to compile a reward function based on the views of the system's stakeholders, and then assess the system again using these more credible rewards. Future research could also focus on gathering more data about the agent/patient and employ the inverse reinforcement learning to compile the reward function. The inverse reinforcement learning is the field of learning an agent's objectives, values, or rewards by observing its behavior. Moreover, this research only considered the rewards to the patient. In practice, there are several dimensions to the system, each with an associated reward/cost structure. These can be in conflict/competition with each other. Therefore, there needs to be a treatment of multi-objective decision environment for a more accurate performance assessment of the system. Furthermore, our approach does not account for time-related penalties for late actions, or for time-related changes in the agent itself. The focus of future research could be on assigning penalties (or negative rewards) to activities or tasks that are not executed on time. Another limitation is that our study did not consider probability of the variability of functional outputs. The probability of producing each functional output might be different from others. Considering the probabilities of variable functional outputs can help find the optimal pathway, where negative variations are dampened, and positive variations are amplified.

The effort of coupling reinforcement learning and the FRAM modelling went into identifying the probabilities of connections between functions (nodes). It has similarities with Bayesian networks theory. Each node is a state/function, and each connection is a conditional probability. The probability of the output(s) of each function is determined by a set of input, preconditions, resource, control, and time as well as the interactions of upstream functions with the current function. A limitation of the current PhD research work is to consider the average probability for each connection based on patients' historical data. Future work could also concentrate on reframing the FRAM model as a Bayesian network for probabilistic modelling purposes to consider a conditional probability for each connection in order to improve the accuracy of the proposed model.

Bibliography

Aase, K., & Waring, J. (2020). Crossing boundaries: Establishing a framework for researching quality and safety in care transitions. *Applied Ergonomics*, *89*, 103228.

Aboutorab, H., Hussain, O. K., Saberi, M., & Hussain, F. K. (2022). A reinforcement learning-based framework for disruption risk identification in supply chains. *Future Generation Computer Systems*, *126*, 110–122.

Accou, B., & Reniers, G. (2019). Developing a method to improve safety management systems based on accident investigations: the SAfety FRactal ANalysis. *Safety Science*, *115*, 285–293.

Adriaensen, A, Costantino, F., Di Gravio, G., & Patriarca, R. (n.d.). Teaming with industrial cobots: A socio-technical perspective on safety analysis. *Human Factors and Ergonomics in Manufacturing & Service Industries*.

Adriaensen, Arie, Patriarca, R., Smoker, A., & Bergström, J. (2019). A socio-technical analysis of functional properties in a joint cognitive system: a case study in an aircraft cockpit. *Ergonomics*, *just-accepted*, 1–48.

Aguilera, M. V. C., da Fonseca, B. B., Ferris, T. K., Vidal, M. C. R., & de Carvalho, P. V. R. (2016). Modelling performance variabilities in oil spill response to improve system resilience. *Journal of Loss Prevention in the Process Industries*, *41*, 18–30.

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.

Alboghobeish, A., & Shirali, G. A. (2021). Integration of Functional Resonance Analysis with Multicriteria Analysis for Sociotechnical Systems Risk Management. *Risk Analysis*.

Alvarenga, M. A. B., e Melo, P. F. F., & Fonseca, R. A. (2014). A critical review of methods and models for evaluating organizational factors in Human Reliability Analysis. *Progress in Nuclear Energy*, *75*, 25–41.

Anvarifar, F., Voorendt, M. Z., Zevenbergen, C., & Thissen, W. (2017). An application of the Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood defences in the Netherlands. *Reliability Engineering & System Safety*, *158*, 130–141.

Avlund, K., Jepsen, E., Vass, M., & Lundemark, H. (2002). Effects of comprehensive follow-up home visits after hospitalization on functional ability and readmissions among old patients. A randomized controlled study. *Scandinavian Journal of Occupational Therapy*, *9*(1), 17–22.

Aydon, L., Hauck, Y., Murdoch, J., Siu, D., & Sharp, M. (2018). Transition from hospital to home: parents' perception of their preparation and readiness for discharge with their preterm infant. *Journal of Clinical Nursing*, *27*(1–2), 269–277.

Barnhart, S. L., & Carpenter, A. (2016). Transition from hospital to home. In *Caring for the Ventilator Dependent Child* (pp. 89–119). Springer.

Belmonte, F., Schön, W., Heurley, L., & Capel, R. (2011). Interdisciplinary safety analysis of complex socio-technological systems based on the functional resonance accident model: An application to railway trafficsupervision. *Reliability Engineering & System Safety*, *96*(2), 237–249.

Bergström, J., Van Winsen, R., & Henriqson, E. (2015). On the rationale of resilience in the domain of safety: A literature review. *Reliability Engineering & System Safety*, *141*, 131–141.

Bjerga, T., Aven, T., & Zio, E. (2016). Uncertainty treatment in risk analysis of complex systems: The cases of STAMP and FRAM. *Reliability Engineering & System Safety*, *156*, 203–209.

Braithwaite, J., Wears, R. L., & Hollnagel, E. (2016). *Resilient health care, volume 3: Reconciling work-as-imagined and work-as-done*. CRC Press.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101.

Bridges, K. E., Corballis, P. M., & Hollnagel, E. (2018). "Failure-to-Identify" Hunting Incidents: A Resilience Engineering Approach. *Human Factors*, *60*(2), 141–159.

Buikstra, E., Strivens, E., & Clay-Williams, R. (2020). Understanding variability in discharge planning processes for the older person. *Safety Science*, *121*, 137–146.

Campbell-Sills, L., & Stein, M. B. (2007). Psychometric analysis and refinement of the connor–davidson resilience scale (CD-RISC): Validation of a 10-item measure of resilience. *Journal of Traumatic Stress: Official Publication of The International Society for Traumatic Stress Studies*, *20*(6), 1019–1028.

Carayon, P. (2006). Human factors of complex sociotechnical systems. *Applied ergonomics*, *37*(4), 525-535.

Catchpole, K., & Alfred, M. (2018). Industrial conceptualization of health care versus the naturalistic decision-making paradigm: Work as imagined versus work as done. *Journal of Cognitive Engineering and Decision Making*, *12*(3), 222–226.

Charlson, M. E., Pompei, P., Ales, K. L., & MacKenzie, C. R. (1987). A new method of classifying prognostic comorbidity in longitudinal studies: development and validation. *Journal of Clinical Epidemiology*, *40*(5), 373–383.

Clay-Williams, R., Hounsgaard, J., & Hollnagel, E. (2015). Where the rubber meets the road: using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines. *Implementation Science*, *10*(1), 125.

Connor, K. M., & Davidson, J. R. T. (2003). Development of a new resilience scale:

The Connor-Davidson resilience scale (CD-RISC). *Depression and Anxiety*, *18*(2), 76–82.

Coronato, A., Naeem, M., De Pietro, G., & Paragliola, G. (2020). Reinforcement learning for intelligent healthcare applications: A survey. *Artificial Intelligence in Medicine*, *109*, 101964.

Cosco, T. D., Kaushal, A., Richards, M., Kuh, D., & Stafford, M. (2016). Resilience measurement in later life: a systematic review and psychometric analysis. *Health and Quality of Life Outcomes*, *14*(1), 16.

Costantino, F., Di Gravio, G., & Tronci, M. (2018). Environmental Audit improvements in industrial systems through FRAM. *IFAC-PapersOnLine*, *51*(11), 1155–1161.

Creavin, S. T., Wisniewski, S., Noel-Storr, A. H., Trevelyan, C. M., Hampton, T., Rayment, D., Thom, V. M., Nash, K. J. E., Elhamoui, H., & Milligan, R. (2016). Mini-Mental State Examination (MMSE) for the detection of dementia in clinically unevaluated people aged 65 and over in community and primary care populations. *Cochrane Database of Systematic Reviews*, *1*.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.

Dallat, C., Salmon, P. M., & Goode, N. (2017). Risky systems versus risky people: To what extent do risk assessment methods consider the systems approach to accident causation? A review of the literature. *Safety Science*.

Damen, N. L., de Vos, M. S., Moesker, M. J., Braithwaite, J., van Wijngaarden, R. A. F. de L., Kaplan, J., Hamming, J. F., & Clay-Williams, R. (2019). Preoperative anticoagulation management in everyday clinical practice: an international comparative analysis of work-as-done using the functional resonance analysis method. *Journal of Patient Safety*.

Danial, S. N., Smith, D., & Veitch, B. (2021). A Method to Detect Anomalies in Complex Socio-Technical Operations Using Structural Similarity. *Journal of Marine Science and Engineering*, *9*(2), 212.

De Carvalho, P. V. R. (2011). The use of Functional Resonance Analysis Method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience. *Reliability Engineering & System Safety*, *96*(11), 1482–1498.

de Souza, I. T., Rosa, A. C., Evangelista, A. C. J., Tam, V. W. Y., & Haddad, A. (2021). Modelling the work-as-done in the building maintenance using a layered FRAM: A case study on HVAC maintenance. *Journal of Cleaner Production*, *320*, 128895.

de Vries, L. (2017). Work as done? Understanding the practice of sociotechnical work in the maritime domain. *Journal of Cognitive Engineering and Decision Making*, *11*(3), 270–295.

Dekker, S. (2012). Complexity, signal detection, and the application of ergonomics: Reflections on a healthcare case study. *Applied Ergonomics*, *43*(3), 468–472.

Dekker, S., Cilliers, P., & Hofmeyr, J.-H. (2011). The complexity of failure: implications of complexity theory for safety investigations. *Safety Science*, *49*(6), 939–945.

del Carmen Pardo-Ferreira, M., Rubio-Romero, J. C., Gibb, A., & Calero-Castro, S. (2020). Using functional resonance analysis method to understand construction activities for concrete structures. *Safety Science*, *128*, 104771.

Deutsch, E. S. (2017). Bridging the gap between work-as-imagined and work-as-done. *Pennsylvania Patient Safety Advisory*, *14*(2), 80–83.

Doyle, J., Caprani, N., Kealy, A., Bond, R., Komaba, Y., & Inomata, A. (2016). Healthcare professionals views on technology to support older adults transitioning from hospital to home. *Proceedings of the 30th International BCS Human Computer Interaction Conference 30*, 1–11.

Duan, G., Tian, J., & Wu, J. (2015). Extended FRAM by integrating with model checking to effectively explore hazard evolution. *Mathematical Problems in Engineering*, *2015*.

Ebrahimi, Z., Wilhelmson, K., Eklund, K., Moore, C. D., & Jakobsson, A. (2013). Health despite frailty: exploring influences on frail older adults' experiences of health. *Geriatric Nursing*, *34*(4), 289–294.

Falegnami, A., Costantino, F., Di Gravio, G., & Patriarca, R. (2019). Unveil key functions in socio-technical systems: mapping FRAM into a multilayer network. *Cognition, Technology & Work*, 1–23.

Ferreira, P. N. P., & Cañas, J. J. (2019). Assessing operational impacts of automation using functional resonance analysis method. *Cognition, Technology & Work*, 1–18.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198.

França, J. E. M., Hollnagel, E., dos Santos, I. J. A. L., & Haddad, A. N. (2019). FRAM AHP approach to analyse offshore oil well drilling and construction focused on human factors. *Cognition, Technology & Work*, 1–13.

Fried, L. P., Tangen, C. M., Walston, J., Newman, A. B., Hirsch, C., Gottdiener, J., Seeman, T., Tracy, R., Kop, W. J., & Burke, G. (2001). Frailty in older adults: evidence for a phenotype. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *56*(3), M146–M157.

Fukuda, K., Sawaragi, T., Horiguchi, Y., & Nakanishi, H. (2016). Applying systemic accident model to learn from near-miss incidents of train maneuvering and operation. *IFAC-PapersOnLine*, *49*(19), 543–548.

Furniss, D., Curzon, P., & Blandford, A. (2016). Using FRAM beyond safety: a case study to explore how sociotechnical systems can flourish or stall. *Theoretical Issues in Ergonomics Science*, *17*(5–6), 507–532.

Gao, Y., Fan, Y., Wang, J., & Duan, Z. (2019). Evaluation of governmental safety regulatory functions in preventing major accidents in China. *Safety Science*, *120*, 299–311.

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.

Goins, R. T., Gregg, J. J., & Fiske, A. (2013). Psychometric properties of the Connor-Davidson resilience scale with older American Indians: The native elder care study. *Research on Aging*, *35*(2), 123–143.

Goodfellow, I., Bengio, Y., & Courville, A. (2016). *Deep learning*. MIT press.

Grant, E., Salmon, P. M., Stevens, N. J., Goode, N., & Read, G. J. (2018). Back to the future: What do accident causation models tell us about accident prediction? *Safety Science*, *104*, 99–109.

Hackel, L. M., Mende-Siedlecki, P., & Amodio, D. M. (2020). Reinforcement learning in social interaction: The distinguishing role of trait inference. *Journal of Experimental Social Psychology*, *88*, 103948.

Halasyamani, L., Kripalani, S., Coleman, E., Schnipper, J., Van Walraven, C., Nagamine, J., Torcson, P., Bookwalter, T., Budnitz, T., & Manning, D. (2006). Transition of care for hospitalized elderly patients—development of a discharge checklist for hospitalists. *Journal of Hospital Medicine*, *1*(6), 354–360.

Hegedűs, T., Németh, B., & Gáspár, P. (2019). Graph-based multi-vehicle overtaking strategy for autonomous vehicles. *IFAC-PapersOnLine*, *52*(5), 372–377.

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.

Heuberger, R. A. (2011). The frailty syndrome: a comprehensive review. *Journal of Nutrition in Gerontology and Geriatrics*, *30*(4), 315–368.

Hill, R., & Hollnagel, E. (2016). *Instructions for use of the FRAM Model Visuliser (FMV)*.

Hirose, T., & Sawaragi, T. (2020). Extended FRAM model based on cellular automaton to clarify complexity of socio-technical systems and improve their safety. *Safety Science*, *123*, 104556.

Hirose, T., Sawaragi, T., & Horiguchi, Y. (2016). Safety analysis of aviation flight-deck procedures using systemic accident model. *IFAC-PapersOnLine*, *49*(19), 19–24.

Holden, R. J., Carayon, P., Gurses, A. P., Hoonakker, P., Hundt, A. S., Ozok, A. A., & Rivera-Rodriguez, A. J. (2013). SEIPS 2.0: a human factors framework for studying and improving the work of healthcare professionals and patients. *Ergonomics*, *56*(11), 1669–1686.

Holden, R. J., & Mickelson, R. S. (2013). Performance barriers among elderly chronic heart failure patients: An application of patient-engaged human factors and ergonomics. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *57*(1), 758–762.

Holland, D. E., Conlon, P. M., Rohlik, G. M., Gillard, K. L., Messner, P. K., & Mundy, L. M. (2015). Identifying hospitalized pediatric patients for early discharge planning: A feasibility study. *Journal of Pediatric Nursing*, *30*(3), 454–462.

Hollnagel, E. (2009). *The ETTO principle: efficiency-thoroughness trade-off: why things that go right sometimes go wrong*. Ashgate Publishing, Ltd.

Hollnagel, E. (2012a). Coping with complexity: past, present and future. *Cognition, Technology & Work*, *14*(3), 199–205.

Hollnagel, E. (2012b). *FRAM, the functional resonance analysis method: modelling complex socio-technical systems*. Ashgate Publishing, Ltd.

Hollnagel, E. (2016). *Barriers and accident prevention*. Routledge.

Hollnagel, E. (2017). *FRAM: the functional resonance analysis method: modelling complex socio-technical systems*. CRC Press.

Hollnagel, E. (2018). *Safety-I and safety-II: the past and future of safety management*. CRC press.

Hollnagel, E., & Braithwaite, J. (2019). *Resilient health care*. CRC Press.

Hounsgaard, J. (2016). *Patient Safety in Everyday Work: Learning from things that go right*. Syddansk Universitet.

Huang, W., Shuai, B., Zuo, B., Xu, Y., & Antwi, E. (2019). A systematic railway dangerous goods transportation system risk analysis approach: The 24 model. *Journal of Loss Prevention in the Process Industries*.

Huang, W., Yin, D., Xu, Y., Zhang, R., & Xu, M. (2021). Using NK Model to quantitatively calculate the variability in Functional Resonance Analysis Method. *Reliability Engineering & System Safety*, 108058.

Hulme, A., Stanton, N. A., Walker, G. H., Waterson, P., & Salmon, P. M. (2019). What do applications of systems thinking accident analysis methods tell us about accident causation? A systematic review of applications between 1990 and 2018. *Safety Science*, *117*, 164–183.

Hwang, G. H., & Yoon, W. C. (2020). A new approach to requirement development for a common operational picture to support distributed situation awareness. *Safety Science*, *125*, 104569.

Jensen, A., & Aven, T. (2017). Hazard/threat identification: Using functional resonance analysis method in conjunction with the Anticipatory Failure Determination method. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *231*(4), 383–389.

Jensen, A., & Aven, T. (2018). A new definition of complexity in a risk analysis setting. *Reliability Engineering & System Safety*, *171*, 169–173.

Kaptan, M., Sarıalioğlu, S., Uğurlu, Ö., & Wang, J. (2021). The evolution of the HFACS method used in analysis of marine accidents: A review. *International Journal of Industrial Ergonomics*, *86*, 103225.

Katz, J. N., Chang, L. C., Sangha, O., Fossel, A. H., & Bates, D. W. (1996). Can comorbidity be measured by questionnaire rather than medical record review? *Medical Care*, 73–84.

Kaya, G. K., Ovali, H. F., & Ozturk, F. (2019). Using the functional resonance analysis method on the drug administration process to assess performance variability. *Safety Science*, *118*, 835–840.

Kaya, G. K., Ozturk, F., & Sariguzel, E. E. (2021). System-based risk analysis in a tram operating system: integrating Monte Carlo simulation with the functional resonance analysis method. *Reliability Engineering & System Safety*, 107835.

Kianfar, S., Carayon, P., Hundt, A. S., & Hoonakker, P. (2019). Care coordination for chronically ill patients: identifying coordination activities and interdependencies. *Applied Ergonomics*, *80*, 9–16.

Kim, Y. C., & Yoon, W. C. (2021). Quantitative representation of the functional resonance analysis method for risk assessment. *Reliability Engineering & System Safety*, *214*, 107745.

Klar, M., Glatt, M., & Aurich, J. C. (2021). An implementation of a reinforcement learning based algorithm for factory concept layout planning. *Manufacturing Letters*.

Laugaland, K., Aase, K., & Barach, P. (2012). Interventions to improve patient safety in transitional care–a review of the evidence. *Work*, *41*(Supplement 1), 2915–2924.

Laugaland, K., Aase, K., & Waring, J. (2014). Hospital discharge of the elderly-an observational case study of functions, variability and performance-shaping factors. *BMC Health Services Research*, *14*(1), 365.

Lawton, M. P., & Brody, E. M. (1969). Assessment of older people: self-maintaining and instrumental activities of daily living. *The Gerontologist*, *9*(3_Part_1), 179–186.

Lee, J., & Chung, H. (2018). A new methodology for accident analysis with human and system interaction based on FRAM: Case studies in maritime domain. *Safety Science*, *109*, 57–66.

Lee, J., Yoon, W. C., & Chung, H. (2019). Formal or informal human collaboration approach to maritime safety using FRAM. *Cognition, Technology & Work*, 1–15.

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

Li, T.-H., Wang, Z.-S., Lu, W., Zhang, Q., & Li, D.-F. (2021). Electronic health records based reinforcement learning for treatment optimizing. *Information Systems*, 101878.

Li, W., He, M., Sun, Y., & Cao, Q. (2019). A proactive operational risk identification and analysis framework based on the integration of ACAT and FRAM. *Reliability Engineering & System Safety*, *186*, 101–109.

Liang, X., & Meng, X. (2019). An extended FTOPSIS method for freeway route selection in the pre-feasibility study stage. *Physica A: Statistical Mechanics and Its Applications*, *526*, 120871.

Lundblad, K., Speziali, J., Woltjer, R., & Lundberg, J. (2008). FRAM as a risk assessment method for nuclear fuel transportation. *Proceedings of the 4th International Conference Working on Safety*, *1*, 221–223.

Macchi, L., Hollnagel, E., & Leonhard, J. (2009). *Resilience Engineering approach to safety assessment: an application of FRAM for the MSAW system.*

McNab, D., Freestone, J., Black, C., Carson-Stevens, A., & Bowie, P. (2018). Participatory design of an improvement intervention for the primary care management of possible sepsis using the Functional Resonance Analysis Method. *BMC Medicine*, *16*(1), 174.

Moorkamp, M., Kramer, E.-H., Van Gulijk, C., & Ale, B. (2014). Safety management theory and the expeditionary organization: A critical theoretical reflection. *Safety Science*, *69*, 71–81.

Nuernberger, K., Atkinson, S., & MacDonald, G. (2018). Seniors in Transition: Exploring Pathways Across the Care Continuum. *Healthcare Quarterly*, *21*(1).

O'Hara, J. K., Baxter, R., & Hardicre, N. (2020). 'Handing over to the patient': A FRAM analysis of transitional care combining multiple stakeholder perspectives. *Applied Ergonomics*, *85*, 103060.

Oeppen, J., & Vaupel, J. W. (2004). Demography. Broken limits to life expectancy. Science of human ageing. *FEBS Lett*, *571*, 243–247.

Olawoyin, A., & Chen, Y. (2018). Predicting the future with artificial neural network. *Procedia Computer Science*, *140*, 383–392.

Organization, W. H. (2015). *World report on ageing and health*. World Health Organization.

Palmer Jr, H. C., Armistead, N. S., Elnicki, D. M., Halperin, A. K., Ogershok, P. R., Manivannan, S., Hobbs, G. R., & Evans, K. (2001). The effect of a hospitalist service with nurse discharge planner on patient care in an academic teaching hospital. *The American Journal of Medicine*, *111*(8), 627–632.

Pardo-Ferreira, M. C., Martínez-Rojas, M., Salguero-Caparrós, F., & Rubio-Romero, J. C. (2019). Evolution of the Functional Resonance Analysis Method (FRAM) through the combination with other methods. *Dirección y Organización*, 41–50.

Patriarca, R., & Bergström, J. (2017). Modelling complexity in everyday operations: functional resonance in maritime mooring at quay. *Cognition, Technology & Work*, *19*(4), 711–729.

Patriarca, R., Bergström, J., & Di Gravio, G. (2017). Defining the functional resonance analysis space: Combining Abstraction Hierarchy and FRAM. *Reliability Engineering & System Safety*, *165*, 34–46.

Patriarca, R., Di Gravio, G., & Costantino, F. (2017a). A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. *Safety Science*, *91*, 49–60.

Patriarca, R., Di Gravio, G., & Costantino, F. (2017b). myFRAM: An open tool support for the functional resonance analysis method. *2017 2nd International Conference on System Reliability and Safety (ICSRS)*, 439–443.

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.

Patriarca, R., Di Gravio, G., Woltjer, R., Costantino, F., Praetorius, G., Ferreira, P., & Hollnagel, E. (2020). Framing the FRAM: A literature review on the functional resonance analysis method. *Safety Science*, *129*, 104827.

Patriarca, R., Falegnami, A., Costantino, F., & Bilotta, F. (2018). Resilience engineering for socio-technical risk analysis: Application in neuro-surgery. *Reliability Engineering & System Safety*, *180*, 321–335.

Pereira, A. G. (2013). *Introduction to the Use of FRAM on the effectiveness assessment of a radiopharmaceutical Dispatches process*.

Pickup, L., Atkinson, S., Hollnagel, E., Bowie, P., Gray, S., Rawlinson, S., & Forrester, K. (2017). Blood sampling-Two sides to the story. *Applied Ergonomics*, *59*, 234–242.

Piera, M. A., Ramos, J. J., & Muñoz, J. L. (2019). A socio-technical holistic agent based model to assess cockpit supporting tools performance variability. *IFAC-PapersOnLine*, *52*(11), 122–127.

Praetorius, G., Graziano, A., Schröder-Hinrichs, J.-U., & Baldauf, M. (2017). Fram in FSA—Introducing a function-based approach to the formal safety assessment framework. In *Advances in Human Aspects of Transportation* (pp. 399–411). Springer.

Praetorius, G., Hollnagel, E., & Dahlman, J. (2015). Modelling Vessel Traffic Service to understand resilience in everyday operations. *Reliability Engineering & System Safety*, *141*, 10–21.

Raben, D. C., Bogh, S. B., Viskum, B., Mikkelsen, K. L., & Hollnagel, E. (2018). Learn from what goes right: A demonstration of a new systematic method for identification of leading indicators in healthcare. *Reliability Engineering & System Safety*, *169*, 187–198.

Raben, D. C., Viskum, B., Mikkelsen, K. L., Hounsgaard, J., Bogh, S. B., & Hollnagel, E. (2018). Application of a non-linear model to understand healthcare processes: using the functional resonance analysis method on a case study of the early detection of sepsis. *Reliability Engineering & System Safety*, *177*, 1–11.

Ragosta, M., Martinie, C., Palanque, P., Navarre, D., & Sujan, M. A. (2015). Concept maps for integrating modeling techniques for the analysis and re-design of partly-autonomous interactive systems. *Proceedings of the 5th International Conference on Application and Theory of Automation in Command and Control Systems*, 41–52.

Randriambelonoro, M., Perrin, C., Blocquet, A., Kozak, D., Fernandez, J. T., Marfaing, T., Bolomey, E., Benhissen, Z., Frangos, E., & Geissbuhler, A. (2020). Hospital-to-Home Transition for Older Patients: Using Serious Games to Improve the Motivation for Rehabilitation–a Qualitative Study. *Journal of Population Ageing*, 1–19.

Ransolin, N., Saurin, T. A., & Formoso, C. T. (2020). Integrated modelling of built environment and functional requirements: Implications for resilience. *Applied Ergonomics*, *88*, 103154.

Rennke, S., Nguyen, O. K., Shoeb, M. H., Magan, Y., Wachter, R. M., & Ranji, S. R. (2013). Hospital-initiated transitional care interventions as a patient safety strategy: a systematic review. *Annals of Internal Medicine*, *158*(5_Part_2), 433–440.

Resnick, B., Zimmerman, S. I., Magaziner, J., & Adelman, A. (1998). Use of the Apathy Evaluation Scale as a measure of motivation in elderly people. *Rehabilitation Nursing*, *23*(3), 141–147.

Riccardo, P., Gianluca, D. P., Giulio, D. G., & Francesco, C. (2018). FRAM for systemic accident analysis: a matrix representation of functional resonance. *International Journal of Reliability, Quality and Safety Engineering*, *25*(01), 1850001.

Righi, A. W., & Saurin, T. A. (2015). Complex socio-technical systems: Characterization and management guidelines. *Applied Ergonomics*, *50*, 19–30.

Robinson, C. A., Bottorff, J. L., Lilly, M. B., Reid, C., Abel, S., Lo, M., & Cummings, G. G. (2012). Stakeholder perspectives on transitions of nursing home residents to hosRobinson, C. A., Bottorff, J. L., Lilly, M. B., Reid, C., Abel, S., Lo, M., & Cummings, G. G. (2012). Stakeholder perspectives on transitions of nursing home residents to hospital eme. *Journal of Aging Studies*, *26*(4), 419–427.

Rockwood, K., Song, X., MacKnight, C., Bergman, H., Hogan, D. B., McDowell, I., & Mitnitski, A. (2005). A global clinical measure of fitness and frailty in elderly people. *Cmaj*, *173*(5), 489–495.

Roffman, C., Buchanan, J., & Allison, G. (2016). Charlson comorbidities index. *Journal of Physiotherapy*, *62*(3).

Roland, D. (2018). Guideline developers are not the only experts: Utilising the FRAM method in sepsis pathways. *BMC Medicine*, *16*(1), 213.

Rosa, L. V., Haddad, A. N., & de Carvalho, P. V. R. (2015). Assessing risk in sustainable construction using the Functional Resonance Analysis Method (FRAM). *Cognition, Technology & Work*, *17*(4), 559–573.

Ross, A., Sherriff, A., Kidd, J., Gnich, W., Anderson, J., Deas, L., & Macpherson, L. (2018). A systems approach using the functional resonance analysis method to support fluoride varnish application for children attending general dental practice. *Applied Ergonomics*, *68*, 294–303.

Ross, S. M. (2014). *Introduction to probability models*. Academic press.

Rosso, C. B., & Saurin, T. A. (2018). The joint use of resilience engineering and lean production for work system design: a study in healthcare. *Applied Ergonomics*, *71*, 45–56.

Rytter, L., Jakobsen, H. N., Rønholt, F., Hammer, A. V., Andreasen, A. H., Nissen, A., & Kjellberg, J. (2010). Comprehensive discharge follow-up in patients' homes by GPs and district nurses of elderly patients: A randomized controlled trial. *Scandinavian Journal of Primary Health Care*, *28*(3), 146–153.

Saldaña, J. (2015). *The coding manual for qualitative researchers*. Sage.

Salehi, V., Veitch, B., & Musharraf, M. (2020). Measuring and improving adaptive capacity in resilient systems by means of an integrated DEA-Machine learning approach. *Applied Ergonomics*, *82*. https://doi.org/10.1016/j.apergo.2019.102975

Salehi, V., Veitch, B., & Smith, D. (2020). Modeling complex socio-technical systems using the FRAM: A literature review. *Human Factors and Ergonomics In Manufacturing*. https://doi.org/10.1002/hfm.20874

Salehi, Vahid, Hanson, N., Smith, D., McCloskey, R., Jarrett, P., & Veitch, B. (2021). Modeling and analyzing hospital to home transition processes of frail older adults using the functional resonance analysis method (FRAM). *Applied Ergonomics*, *93*, 103392.

Salehi, Vahid, Smith, D., Veitch, B., & Hanson, N. (2021). A dynamic version of the FRAM for capturing variability in complex operations. *MethodsX*, *8*, 101333.

Salehi, Vahid, Veitch, B., & Smith, D. (2021). Modeling complex socio-technical systems using the FRAM: A literature review. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *31*(1), 118–142.

Saurin, T. A., & Werle, N. J. B. (2017). A framework for the analysis of slack in socio-technical systems. *Reliability Engineering & System Safety*, *167*, 439–451.

Schutijser, B. C. F. M., Jongerden, I. P., Klopotowska, J. E., Portegijs, S., de Bruijne, M. C., & Wagner, C. (2019). Double checking injectable medication administration: Does the protocol fit clinical practice? *Safety Science*, *118*, 853–860.

Settanni, E., Thenent, N. E., Newnes, L. B., Parry, G., & Goh, Y. M. (2017). Mapping a product-service-system delivering defence avionics availability. *International Journal of Production Economics*, *186*, 21–32.

Sheikh, J. I., & Yesavage, J. A. (1986). Geriatric Depression Scale (GDS): recent evidence and development of a shorter version. *Clinical Gerontologist: The*

Journal of Aging and Mental Health.

Shirali, G. A., & Ebrahipour, V. (2013). Proactive risk assessment to identify emergent risks using functional resonance analysis method (FRAM): A case study in an oil process unit. *Iran Occupational Health*, *10*(6), 33–46.

Shire, M. I., Jun, G. T., & Robinson, S. (2018). The application of system dynamics modelling to system safety improvement: Present use and future potential. *Safety Science*, *106*, 104–120.

Slater, D., Hollnagel, E., MacKinnon, R., Sujan, M., Carson-Stevens, A., Ross, A., & Bowie, P. (2021). A Systems Analysis of the COVID-19 Pandemic Response in the United Kingdom–Part 1-The overall Context. *Safety Science*, 105525.

Smith, D, Veitch, B., Khan, F., & Taylor, R. (2018a). Using FRAM to evaluate ship designs and regulations. In *Marine Design XIII, Volume 2* (pp. 677–683). CRC Press.

Smith, D, Veitch, B., Khan, F., & Taylor, R. (2018b). Using the FRAM to Understand Arctic Ship Navigation: Assessing Work Processes During the Exxon Valdez Grounding. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, *12*.

Smith, Doug, Veitch, B., Khan, F., & Taylor, R. (2017). Understanding industrial safety: Comparing Fault tree, Bayesian network, and FRAM approaches. *Journal of Loss Prevention in the Process Industries*, *45*, 88–101.

Smith, Doug, Veitch, B., Khan, F., & Taylor, R. (2020). Integration of Resilience and FRAM for Safety Management. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *6*(2), 4020008.

Soliman, M., & Saurin, T. A. (2017). Lean production in complex socio-technical systems: a systematic literature review. *Journal of Manufacturing Systems*, *45*, 135–148.

Song, R., Jang, S., Wang, Y., Hanssens, D. M., & Suh, J. (2021). Reinforcement learning and risk preference in equity linked notes markets. *Journal of Empirical Finance*.

Stanton, N. A., Salmon, P. M., Walker, G. H., & Stanton, M. (2019). Models and methods for collision analysis: A comparison study based on the Uber collision with a pedestrian. *Safety Science*, *120*, 117–128.

Stogsdill, M., & Ulfvengren, P. (2017). Mapping risk models/methods onto a complexity spectrum. *Transportation Research Procedia*, *28*, 133–140.

Storm, M., Siemsen, I. M. D., Laugaland, K., Dyrstad, D. N., & Aase, K. (2014). Quality in transitional care of the elderly: Key challenges and relevant improvement measures. *International Journal of Integrated Care*, *14*.

Studic, M., Majumdar, A., Schuster, W., & Ochieng, W. Y. (2017). A systemic modelling of ground handling services using the functional resonance analysis method. *Transportation Research Part C: Emerging Technologies*, *74*, 245–260.

Sutton, R. S., & Barto, A. G. (2018). *Reinforcement learning: An introduction*. MIT press.

Tian, J., Wu, J., Yang, Q., & Zhao, T. (2016). FRAMA: a safety assessment approach based on Functional Resonance Analysis Method. *Safety Science*, *85*, 41–52.

Toroody, A. B., Abaei, M. M., & Gholamnia, R. (2016). Conceptual compression discussion on a multi-linear (FTA) and systematic (FRAM) method in an offshore operation's accident modeling. *International Journal of Occupational Safety and Ergonomics*, *22*(4), 532–540.

Wachs, P., Righi, A. W., & Saurin, T. A. (2018). The Functional Resonance Analysis Method as a Debriefing Tool in Scenario-Based-Training. *Congress of the International Ergonomics Association*, 132–138.

Wachs, P., & Saurin, T. A. (2018). Modelling interactions between procedures and resilience skills. *Applied Ergonomics*, *68*, 328–337.

Watkins, C. J. C. H., & Dayan, P. (1992). Q-learning. *Machine Learning*, *8*(3–4), 279–292.

Williams, S., Nolan, M., & Keady, J. (2009). Relational practice as the key to ensuring quality care for frail older people: discharge planning as a case example. *Quality in Ageing and Older Adults*, *10*(3), 44.

Woltjer, R., & Hollnagel, E. (2008). Functional modeling for risk assessment of automation in a changing air traffic management environment. *Proceedings of the 4th International Conference Working on Safety*, *30*.

Woods, D. D., & Cook, R. I. (2002). Nine steps to move forward from error. *Cognition, Technology & Work*, *4*(2), 137–144.

Yang, Q., Tian, J., & Zhao, T. (2017). Safety is an emergent property: Illustrating functional resonance in Air Traffic Management with formal verification. *Safety Science*, *93*, 162–177.

Yu, M., Quddus, N., Kravaris, C., & Mannan, M. S. (2020). Development of a FRAM-based framework to identify hazards in a complex system. *Journal of Loss Prevention in the Process Industries*, *63*, 103994.

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.

Zhou, Y., Li, B., & Lin, T. R. (2021). Maintenance optimisation of multicomponent systems using hierarchical coordinated reinforcement learning. *Reliability Engineering & System Safety*, 108078.

Zinetullina, A., Yang, M., Khakzad, N., Golman, B., & Li, X. (2021). Quantitative resilience assessment of chemical process systems using functional resonance analysis method and Dynamic Bayesian network. *Reliability Engineering & System Safety*, *205*, 107232.

Appendices

Appendix A

Appendix A.1: Scenarios considered in Chapter 3.

A.1 (Scenario 1): The information provided for patient 1 of city 1.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Stroke/possible dementia	6	I
2	6	Referral to a geriatrician	5	I
3	5	Possible dementia	7	I
4	7	Almost 12 days	8	I
16	8	Hospitalizing at geriatric unit	22	I
19	22	Stroke/Dementia/Pneumonia	35	I
20	22	Nurse assessment	2	I
21	2	Information on dementia	35	P
22	22	SW assessment	11	I
23	11	Social Development Financial Assistance Program	35	P
24	22	Pharmacist assessment	29	I
25	29	Medication reconciliation	35	P
26	22	Physiotherapy	1	I
27	1	Home exercise	35	P
28	22	Occupational therapy	21	I
29	21	Bathroom equipment/Walker	35	P
30	22	Recreation therapy	23	I
31	23	Satisfactory	35	P
34	22	Nutrition therapy	24	I
35	24	Excellent	35	P
36	22	Spiritual care	31	I
37	31	Satisfactory	35	P
38	22	X-ray test	37	I
39	37	Satisfactory	35	P
41	35	Stable situation/Symptoms of mild delirium+pamphlet	9	I
44	9	Informing for family conference	0	I
45	9	Informing for discharge	26	I
46	26	Spouse+daughter,0,P	0	P
47	0	Excellent ability for discharge/Delay	4	I
65	4	Physician follow up for one month later	14	I

66	4	Blister pack medication/home exercise/no discharge planner (social worker)	3	I
67	14	the patient did not attend the arranged follow-up due to hospital admission	3	I
68	3	Unwell	19	I
72	19	Cough	27	I
73	27	More tests	16	I

A.1 (Scenario 2): The information provided for patient 3 of city 1.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Fractured hip/Delirium	6	I
2	6	Referral to a geriatrician	5	I
3	5	Dementia/delay	7	I
14	7	Almost 12 days	8	I
26	8	Hospitalizing in geriatric unit	22	I
27	22	Fractured hip/Delirium	35	I
28	22	Nurse assessment	2	I
29	2	Information on dementia	35	P
30	22	SW assessment	11	I
31	11	Social Development Financial Assistance Program	35	P
32	22	Pharmacist assessment	29	I
33	29	Medication reconciliation	35	P
34	22	Physiotherapy	1	I
35	1	Home exercise	35	P
36	22	Occupational therapy	21	I
37	21	Home care services	35	P
38	22	Recreation therapy	23	I
39	23	Cognitive impairment (Dementia)	35	P
40	22	Nutrition therapy	24	I
41	24	Satisfactory	35	P
42	35	Medication change/Home care services/Home exercise/Safety equipment	9	I
43	9	Informing for family conference	0	I
44	9	Informing for discharge	26	I
45	26	Spouse	0	P
46	0	Acceptable ability for discharge	4	I
47	4	Arranged for one month later	14	I
48	4	Home care services/delay/no	3	I

		discharge planner (social worker)		
52	14	The physician appointment was performed	3	I

A.1 (Scenario 4): The information provided for patient 2 of city 2.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Right MCA stroke with left sided weakness	6	I
2	6	Referral to a geriatrician	5	I
3	5	Hypertension	7	I
4	7	Almost one day	8	I
5	8	Hospitalizing at geriatric unit	22	I
6	22	Coronary Artery Disease/Hypertension/Dyslipidemia	35	I
7	22	Nurse assessment	2	I
9	2	Satisfactory	35	P
10	22	SW assessment	11	I
11	11	Satisfactory	35	P
12	22	Physiotherapy	1	I
13	1	Satisfactory	35	P
14	22	Occupational therapy	21	I
15	21	Satisfactory	35	P
16	22	Speech pathology	30	I
17	30	Satisfactory	35	P
18	22	Ulceration on tongue	37	I
22	37	Satisfactory/delay	35	P
37	35	Aspirin-Fragmin-Gemfibrozil-Lansoprazol-vitamin D-omega-3/delay	9	I
45	35	Stable situation/case coordinator	4	I
46	9	Informing for discharge	26	I
47	26	Spouse	4	P
48	4	Physician follow-up for one week later	14	I
49	4	Medication on transfer/additional home medication/no discharge planner (case coordinator)	3	I
50	14	Physician follow-up was done	3	I

A.1 (Scenario 5): The information provided for patient 1 of city 3.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Dysmobility	6	I
2	6	Referral to emergency department	36	I
3	36	Hospitalizing at emergency department	22	I
5	22	Diabetes/Hypertension/Dyslipidemia/Glaucoma/Osteoarthritis/Rheumatoid Arthritis/Depression/Anemia	35	I
15	22	Nurse assessment	2	I
16	2	Satisfactory	35	P
17	22	Physiotherapy	1	I
18	1	Satisfactory	35	P
19	22	Pain in her wrist and hands	21	I
20	21	Her wrist and hands is satisfactory	35	P
23	22	Diabetes/Hypertension/Glaucoma/Anemia/Bladder scan	37	I
26	37	Satisfactory	35	P
28	35	Acceptable stability in patient's ability	4	I
29	35	Informing for discharge/delay	26	I
31	26	Daughter	4	P
32	4	Physician follow up for seven weeks later/discharge planner	14	I
33	4	Appointment with a gynecologist	3	I
37	14	The appointments with the physician and gynecologist were done	3	I

A.1 (Scenario 6): The information provided for patient 2 of city 3.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Fractured Pelvis/Congestive heart failure	6	I
2	6	Referral to emergency department	36	I
3	36	Hospitalized at emergency department	7	I
7	7	Almost 5 days	8	I
12	8	Hospitalizing at geriatric unit	22	I
13	22	Fractured Pelvis/Congestive Heart Failure/Chronic Renal Failure/Atrial Fibrillation/Hypothyroid/Urinary Tract Infection	35	I
14	22	Nurse assessment	2	I
15	2	Satisfactory	35	P

16	22	Physiotherapy	1	I
17	1	Significant dysmobility	35	P
18	22	Occupational therapy	21	I
19	21	Tilt wheelchair/equipment needs in bathroom	35	P
20	22	Nutrition therapy	24	I
21	24	Stable and satisfactory	35	P
22	35	Stable situation/instructions for blister pack and insulin regime	9	I
23	9	Informing for family conference	0	I
28	9	Informing for discharge with delay	26	I
30	26	Spouse and daughter	0	P
31	0	Acceptable ability for discharge/Delay	4	I
32	4	No documentation of a physician appointment/consulting with a dermatologist for cellulitis	14	I
35	4	Discharge planner	3	I
36	14	The appointment with the dermatologist was done	3	I
37	3	Unwell	19	I
38	19	Congestive heart failure/cellulitis	16	I

Appendix A.2: Functional temporal variability. Videos for capturing time regarding a specific function. To run a video, double click on the video.

<table>
<tr><td>City 1-Patient 1-Time-Waitlist-Video.avi
Video 1: Patient 1 from city 1 (Scenario 1).</td><td>City 2-Patient 2-Time-Waitlist-Video.avi
Video 2: Patient 2 from city 2 (Scenario 4).</td></tr>
<tr><td colspan="2">City 3-Patient 2-Time-Waitlist-Video.avi
Video 3: Patient 2 from city 3 (Scenario 6).</td></tr>
</table>

Appendix A.3: Capturing time in the entire system. To run a video, double click on the video.

City 1-Patient 1.avi

Video 4: Patient 1 from city 1 (Scenario 1).

Appendix A.4: Capturing time in the entire system. To run a video, double click on the video.

City 2-Patient 1.avi

Video 5: Patient 1 from city 2 (Scenario 3).

Appendix B

Appendix B.1: Patient/caregiver interview guide.

1. Can you tell me about your latest experience being admitted to or having someone, you care for admitted to the hospital?
2. What have you been told or were told about going home or the one you care for going home? a. Who told you about going home or the one you care for going home? b. Was there any other information that you would like or would have liked to know? c. What are or were your concerns about the process?
3. What do you think a successful transition from hospital to home means?
4. Is there anything further you would like to tell me?
5. Are there any questions that you think I should be asking?

Appendix B.2: Health care provider interview guide and interdisciplinary team focus group questions.

An introduction about the three phases of the research project will be given and then the following questions discussed with the group/ to the individual:
1. What is the process for a successful transition from hospital to home? o Probe: What are the necessary steps and who do they involve?
2. Do you think the measures we are using will be adequate to capture the challenges patients may have with discharge and/or transitioning to home?
3. Is there anything you think is important that we have not included?
4. Is there anything you would be interested in knowing about patients' transition home after a hospital admission that we have not included in this research?
5. Are there any additional comments or feedback about this project that you would like to share with us?

Appendix B.3: Phase 2 Observation grid template for observations during weekly team meetings in-hospital.

Occupational Group	**Activities Related to Transitions Process** (Guidelines/Policies/Standards; Referral and Admission Processes; Evaluations/Assessments/Monitoring; Goal Attainment; Patient and Family Education; Interdisciplinary team collaboration and communication; Accessibility; Decisions; Plan of Care; Interventions; Timing; Use of Technology; Coordination with the municipal health services/discharge planning; Equipment Needs/Services/Supplies; Medication Reconciliation and Medication Review; Communication with the patient and patient involvement/participation; Coordination with next of kin and Primary Care Provider; Discharge Planning and Discharge Criteria; Documentation and information transfer/sharing; Resources; Issues/Variabilities; Results/Outcomes; Follow-up Care; Quality and Safety; Other Factors related to the transitions process)
[Group specified]	[Field notes]

Appendix B.4: Phase 2 data collection and measures.

Caregiver Pre- and Post-Discharge Semi-Structured Interview Guides. Caregivers of patients participated in semi-structured interviews including questions related to the transition from hospital-to-home process. Interviews were conducted prior to discharge and again at 3 months post-discharge (see Appendix B.5).

Patient Pre- and Post-Discharge Semi-Structured Interview Guides. Patients participated in semi-structured interviews including questions related to the transition from hospital-to-home process. Interviews were conducted prior to discharge and again at 3 months post-discharge (see Appendix B.5).

Patient and Caregiver Home Visit Semi-Structured Interview Guide. Participants participated in brief semi-structured interviews during home visits at one week and one-month post-discharge (see Appendix B.6), and these were audio recorded. Patients and caregivers could decide whether they wanted to participate in these interviews either separately (one-on-one semi-structured interview) or together. The interview questions asked about specific elements of the patient's care plan (e.g., issues, decisions, communication).

Demographic information. Demographic information was collected via separate questionnaires completed by the identified primary caregiver and the patient prior to discharge from hospital. In addition to the demographic information on this form, the following patient information was obtained from the patient's medical record concerning the latest hospital admission: Date of being put on geriatric waitlist; date of hospital and geriatric unit admission; reason for hospital and geriatric unit admission; diagnoses; baseline clinical frailty score (if collected upon admission to the unit); Mini Mental Status Examination score (MMSE; if completed upon hospital admission); discharge dates; and, documentation associated with care transitions, including consultations placed to community agencies by hospital staff and discharge instructions. If the MMSE was completed upon hospital admission, this score was pulled from the patient's chart and the MMSE was not completed at discharge.

Clinical Frailty. Participants' levels of frailty was measured using the Clinical Frailty Scale (CFS) (Rockwood et al., 2005). Completion of this scale is based on clinical judgment, and responses are recorded on a 9-point Likert scale (1 = *very fit*; 9 = *terminally ill*). The CFS has demonstrated inter-rater reliability, is easy to use and can be readily administered in a clinical setting (Rockwood et al., 2005).

Cognitive Impairment. The Mini-Mental Status Examination (MMSE) (Folstein et al., 1975) is a widely used measure to screen for cognitive impairment in older adults. This measure consists of 11 questions to assess the following cognitive functions: orientation; registration; attention and calculation; recall; and language. Total scores range from 0 to 30, and a score of < 24 can be indicative of cognitive impairment (Creavin et al., 2016). The MMSE is a valid and reliable test of cognitive impairment (Folstein et al., 1975) that has been extensively used in both clinical practice and research.

Depression. The Geriatric Depression Scale-15 (GDS) (Sheikh & Yesavage, 1986) is a measure of depression specifically designed for older adults. The GDS-15 is the short form of the GDS-30, and was developed by selecting 15 items on the GDS-30 that correlated the most highly with symptoms of depression (Sheikh & Yesavage, 1986). Respondents are asked to respond "Yes" or "No" to all 15 items (e.g., *Are you basically satisfied with your life*?, *Do you feel that your situation is hopeless*?) to indicate how they felt over the last week. A total score is calculated by summing all responses, and higher scores are indicative of greater levels of depression. This scale is a valid and reliable assessment for measuring depression in older adults who are either healthy, physically ill, or mild to moderately cognitively impaired (Sheikh & Yesavage, 1986).

Instrumental Activities of Daily Living. The Instrumental Activities of Daily Living Scale (IADL) (Lawton & Brody, 1969) scale is a widely used measure to assess an individual's living skills. An individual's ability to perform the following eight domains of functioning are assessed: ability to use the telephone; shopping; food preparation; housekeeping; laundry; mode of transportation; responsibility for own medications; and, ability to handle finances. A summary score ranges from 0 (*low function, dependent*) to 8 (*high function, independent*). The IADL has demonstrated good inter-rater reliability, and validity with four distinct assessments that measure the domains of functional status (Lawton & Brody, 1969).

Physical Self-Maintenance. The Physical Self-Maintenance Scale (PSMS) (Lawton & Brody, 1969) is a tool used to assess an individual's ability to perform the following self-care activities: toileting; feeding; dressing; grooming; physical ambulation; and, bathing. A summary score ranges from 0 (*complete dependence*) to 6 (*complete independence*). The PSMS has demonstrated good inter-rater reliability, and validity with four distinct assessments that measure the domains of functional status (Lawton & Brody, 1969).

Apathy. The Apathy Evaluation Scale-7 (AES-7) (Resnick et al., 1998) is a measure of apathy that was specifically developed for older adults. Responses are scored on a 4-point Likert scale, with responses ranging from "*Very True*" to "*Not at all true*". Higher scores are indicative of a greater level of apathy, or lower motivation. A modified caregiver version of this scale was used in this study. The shortened version of this scale has demonstrated adequate internal consistency (Chronbach's alpha = 0.67) and construct and incremental validity, suggesting that it can be used in place of the longer 18-item AES (Resnick et al., 1998).

Resiliency. Family caregiver and patient resiliency, or the ability to adapt to adversity, was measured using the Shortened Connor-Davidson Resilience Scale (CD-RISC10) (Campbell-Sills & Stein, 2007; Connor & Davidson, 2003). The CD-RISC10 consists of 10-items and responses are recorded on a 5-point Likert scale (0 = *not true at all*; 4 = *true nearly all of the time*), whereby higher scores reflect greater resilience. Questions address the participant's ability to adapt or deal with adversity. This scale has demonstrated good construct validity and internal reliability in a sample of older adults (Chronbach's alpha = .88) (Goins et al., 2013) and undergraduate students (Chronbach's alpha = .85) (Campbell-Sills & Stein, 2007). The longer version of this scale (CD-RISC) (Connor & Davidson, 2003) has been used to measure resilience in family caregivers in previous research (Campbell-Sills & Stein, 2007). Moreover, a systematic review and psychometric analysis by Cosco et al. (2016) concluded that the CD-RISC10 demonstrates psychometric robustness and is appropriate for use with older adults. This measure was completed by patients and family caregivers prior to hospital discharge and again at 3 months following discharge. Aside from its good psychometric properties, the shortened version of this scale was selected given that measuring resilience is not a main focus of this study, and to reduce the burden on caregivers and patients.

Participant comorbidity. Each participants' level of comorbidity was measured using the self-report Charlson Comorbidity Index, also known as the Comorbidity Questionnaire (SR-CCI) (Katz et al., 1996). The CCI is an extensively validated measure developed to determine mortality risk and burden of disease (Roffman et al., 2016), and has been used in clinical practice to classify participants based on disease severity. Due to the prospective nature of this study, the SR-CCI was used and performed as an interview. Previous studies have found that the SR-CCI is a reproducible and valid measure of comorbidity (Katz et al., 1996). The average interview duration for this measure is 10 minutes per participant (Roffman et al., 2016). In addition, the SR-CCI has been demonstrated to have high test re-test reliability (Katz et al., 1996; Roffman et al., 2016). The SR-CCI was weighted and scored according to the algorithm proposed by Katz et al. (1996), which is consistent with the scoring of the medical record-based CCI (Charlson et al., 1987) with the single exception of liver disease (unlike the medical record-based CCI, the SR-CCI does not distinguish between mild and serious liver disease).

Health care utilization. The patient participants' health care utilization was measured prospectively. At time of hospital discharge, both the participant and their caregiver were provided with a Health Care Utilization form and instructions for keeping track of the patient's utilization. During each home visit, this information was collected from the participant by the Research Nurse.

Appendix B.5: Phase 2 semi-structured interview guides.

Pre-discharge semi-structured interview guides

Patient

1. Why were you admitted to the hospital?
2. How do you feel about being in the hospital?
3. Can you tell me about the care you've had in the hospital?
4. Have you been actively involved in decisions about your care?
5. Can you tell me about your discharge from the hospital?
6. What sort of information have you been given about your discharge from the hospital?
    a. Who told you this information?
    b. What sort of supports or help do you have set up?
    c. Did you have any help before you were admitted to the hospital?
    d. How have you been involved in the discharge plans?
7. How do you feel about going home?
    a. Do you have any concerns?
    b. Do you feel prepared?
8. Is there anything else you would like to add?

Caregiver

1. What is your relationship with [patient's name]?
2. What kind of help did you give them before they were admitted to the hospital?
    a. How many hours a week did you help them?
    b. Did [patient's name] have anyone else helping them?
3. Can you tell me about [patient's name] discharge from hospital?
    a. What sort of information have you been given?
    b. Who told you this information?
    c. What sort of supports or help are set up for them?
    d. How will you help [patient's name] once they are discharged from hospital?
4. How do you feel about [patient's name] going home?
    a. Do you have any concerns?
    b. Do you feel prepared?
5. Do you have any concerns about your own health?
6. Is there anything else you would like to add?

Three-month follow-up semi-structured interview guides:

Patient

1. How have you been making out at home since I last saw you two months ago?
    a. What sort of help do you have around the house?
        i. Has it changed since I last saw you?

b. What has your health been like since you left the hospital?
    i. Are there any health issues that you've been worried about?
    ii. Where are you seeking care for these issues?

2. Is there anything you would have liked to happen differently in coming home from the hospital?
    a. What could have made the transition easier?
    b. What was helpful?
3. Is there anything else we should know about being discharged from hospital?

Caregiver

1. How has [patient's name] been making out since I spoke to you last?
    a. What has their health been like since leaving the hospital?
2. How have you been making out caring for them since leaving the hospital?
    a. Do you have anyone supporting you?
    b. Are there other supports for [patient's name] in place?
    c. How has your health been?
3. Is there anything you would have liked to happen differently in the transition from hospital to home?
    a. What was helpful in the transition from hospital to home?
4. Is there anything else you would like to add?

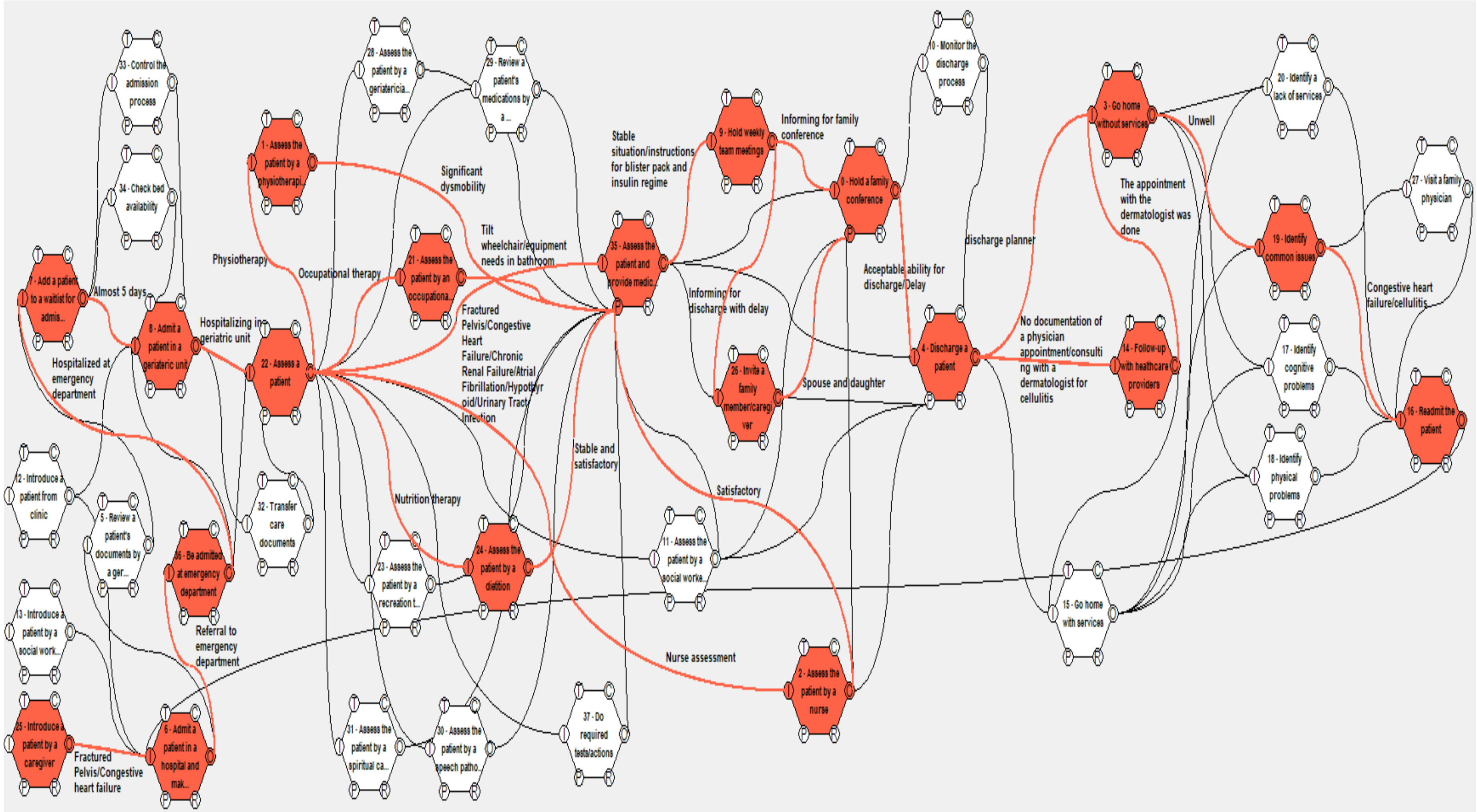
Appendix B.6: Phase 2 patient and caregiver home visit semi-structured interview guide.

(Conducted at one week and one-month post-discharge)

1. How have you been managing since discharge from the hospital?
    a. How are you making out with the medications?
    b. How are you doing with the other instructions on your discharge plan?
    c. What kind of support is there for home care?
        i. Has this changed?
    d. How are you managing daily activities?
        i. Can you tell me about an average day?
    e. How have you been feeling?
        i. Is there anything worrying you?
        ii. What has been going well?

Appendix B.7: The information of a scenario provided for patient 2 of city 3.

Time	Active Function	Active Function Output	Downstream Coupled Function	Coupled Function Aspect
1	25	Fractured Pelvis/Congestive heart failure	6	I
2	6	Referral to emergency department	36	I
3	36	Hospitalized at emergency department	7	I
7	7	Almost 5 days	8	I
12	8	Hospitalizing in geriatric unit	22	I
13	22	Fractured Pelvis/Congestive Heart Failure/Chronic Renal Failure/Atrial Fibrillation/Hypothyroid/Urinary Tract Infection	35	I
14	22	Nurse assessment	2	I
15	2	Satisfactory	35	P
16	22	Physiotherapy	1	I
17	1	Significant dysmobility	35	P
18	22	Occupational therapy	21	I
19	21	Tilt wheelchair/equipment needs in bathroom	35	P
20	22	Nutrition therapy	24	I
21	24	Stable and satisfactory	35	P
22	35	Stable situation/instructions for blister pack and insulin regime	9	I
23	9	Informing for family conference	0	I
28	9	Informing for discharge with delay	26	I
30	26	Spouse and daughter	0	P
31	0	Acceptable ability for discharge/Delay	4	I
32	4	No documentation of a physician appointment/consulting with a dermatologist for cellulitis	14	I
35	4	discharge planner	3	I
36	14	The appointment with the dermatologist was done	3	I
37	3	Unwell	19	I
38	19	Congestive heart failure/cellulitis	16	I



Appendix B.8: An example of an unsuccessful outcome (patient 2 from city 3).

Appendix B.9: A summary of functions' outputs and variability observed during testing the FRAM model for each patient.

Function / Patient's no.	Add a patient to the waitlist for admission	Assess the patient and provide medical services	Hold family conference	Discharge a patient	Follow-up with healthcare providers
City 1: patient 1	**On time:** it lasted 12 days.	**Acceptable:** stable situation and acceptable ability for discharge (symptoms of mild delirium and pamphlet). Treatment and service: home exercise, bathroom equipment, walker, x-ray test. Care team members*: MD, nurse, SW, PT, OT, RT, pharmacist, dietitian, SC.	**Late:** completed with delay. **Acceptable:** excellent ability for discharge. Going home without services not because of financial problems.	**On time:** completed with delay. **Acceptable:** blister pack medication, home exercise, follow-up appointment was arranged by Ward Clerk for one month's time. No discharge planner (social worker played the role).	**Omitted:** the patient did not attend the arranged follow-up due to hospital admission.
City 1: patient 3	**On time:** it lasted 12 days.	**Acceptable:** stable situation and acceptable ability for discharge. Treatment and service: medication change, home care services, home exercise, safety equipment. Care team members: MD, nurse, SW, PT, OT, RT, dietitian.	**On time:** completed on time. **Acceptable:** acceptable ability for discharge. Going home with limited services (daycare assistant) due to financial problems.	**Late:** completed with delay. **Acceptable:** blister pack medication, home exercise, follow-up appointment was arranged by Ward Clerk for one month's time. No discharge planner (social worker played the role).	**Precise:** there was an appointment with the family physician.
City 2: patient 1	**On time:** it lasted 12 days.	**Acceptable:** stable situation and acceptable ability for discharge. Treatment and service: wheelchair, blister pack. Care team members: MD, nurse, SW, PT, OT, RT, dietitian.	**Late:** completed with delay. **Acceptable:** acceptable ability for discharge. Going home without services due to financial problems.	**On time:** completed without delay. **Acceptable:** wheelchair, blister pack, Extra Mural Program with a physiotherapist. No discharge planner (case coordinator played the role).	**Precise:** physiotherapist visited the participant in their home.

City 2: patient 2	**On time:** it lasted one day, short waitlist.	**Acceptable:** stable situation and acceptable ability for discharge. Treatment and service: medication on transfer, additional home medication, ulceration on tongue. Care team members: MD, nurse, SW, PT, OT, SP.	**Omitted:** no family meeting but weekly team meeting was held.	**On time:** completed without delay. **Acceptable:** medication on transfer, additional home medication, follow-up appointment was arranged for one week later. No discharge planner (case coordinator played the role).	**Precise:** there was an appointment with the family physician.
City 3: patient 1	**Omitted:** hospitalized directly at emergency department.	**Acceptable:** Acceptable stability in patient's ability for discharge. Service: diabetes, hypertension, glaucoma, and anemia tests, bladder scan. Care team members: MD, nurse, SW, PT.	**Omitted:** informing directly for discharge.	**Late:** completed with delay. **Acceptable:** appointment arranged with a gynecologist, follow up appointment was arranged by Ward Clerk for seven weeks later. There was discharge planner.	**Precise:** there was an appointment with the family physician and the gynecologist.
City 3: patient 2	**On time:** it lasted five days, short waitlist.	**Acceptable:** relatively stable situation for discharge. Treatment and service: tilt wheelchair, equipment needs in bathroom, instructions for blister pack and insulin regime. Care team members: MD, nurse, PT, OT, dietitian.	**Late:** completed with delay. **Acceptable:** acceptable ability for discharge.	**On time:** completed without delay. **Acceptable:** instructions for blister pack and insulin regime, no documentation of a physician follow-up arranged by hospital staff, consulting with a dermatologist for cellulitis. There was discharge planner, no services at home.	**Precise:** there was an appointment with the dermatologist.

[*] MD: medical doctor, SW: social worker, PT: physiotherapist, OT: occupational therapist, RT: recreation therapist, SC: spiritual care.