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Furniss, Dominic, Nelson, David, Habli, Ibrahim orcid.org/0000-0003-2736-8238 et al. (4 more authors) (2020) Using FRAM to explore sources of performance variability in intravenous infusion administration in ICU:a non- normative approach to systems contradictions. Applied ergonomics. 103113. ISSN 0003-6870

https://doi.org/10.1016/j.apergo.2020.103113

Using FRAM to explore sources of performance variability in intravenous infusion administration in ICU: A non-normative approach to systems contradictions

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Funding

This work is supported by the Assuring Autonomy International Programme, a partnership between Lloyd's Register Foundation and the University of York.

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Abstract

Systems contradictions present challenges that need to be effectively managed, e.g. due to conflicting rules and advice, goal conflicts, and mismatches between demand and capacity. We apply FRAM (Functional Resonance Analysis Method) to intravenous infusion practices in an intensive care unit (ICU) to explore how tensions and contradictions are managed by people. A multi-disciplinary team including individuals from nursing, medical, pharmacy, safety, IT and human factors backgrounds contributed to this analysis. A FRAM model investigation resulting in seven functional areas are described. A tabular analysis highlights significant areas of performance variability, e.g. administering medication before a prescription, prioritising drugs, different degrees of double checking and using sites showing early signs of infection for intravenous access. Our FRAM analysis has been non-normative: performance variability is not necessarily wanted or unwanted, it is merely necessary where system contradictions cannot be easily resolved and so adaptive capacity is required to cope.

Keywords: FRAM; Infusion; Critical Care.

1 Introduction

Intravenous infusion administration is a safety critical task that is common in modern hospitals with high levels of discrepancies and errors (Schnock et al., 2017; Lyons et al., 2018). The details and benefits of technological solutions like smart pumps (Schnock et al., 2017; Lyons et al., 2018), closed-loop systems (Furniss et al., 2019a) and other forms of automation are being explored (Sujan et al., 2019b). However, recent research suggests that this area is a complex adaptive system where interventions do not have a simple deterministic effect but locally appropriate solutions could improve safety (Blandford et al., 2019). This means that complex sociotechnical interactions need to be examined to understand how everyday performance variability emerges, e.g. between structure and agency (Furniss et al., 2019b). A recent special issue on Resilient Health Care in the journal Safety Science (Hollnagel et al., 2019) included several papers that demonstrated how FRAM might be used to describe and to understand performance variability in healthcare settings. For example, FRAM has already been applied to show some of the complexity of drug administration on a neonatal intensive care unit in Turkey, which gives examples of error occurrence and recovery (Kaya et al., 2019). FRAM has been applied to understand the variability in the double-checking procedures for injectable medicines in the Netherlands, which described barriers and facilitators as to why these checks are not performed correctly (Schutijser et al., 2019). It has also been applied to understand workarounds when managing the co-administration of infusions in ICU, e.g. when there are compatibility issues and inadequate venous access (Oduyale et al., 2020). We build on these

examples to use FRAM to explore sources of performance variability for intravenous infusion administration in an intensive care unit (ICU) in England, focusing on sources of performance variability and underlying systems contradictions.

2 Background

Resilience is defined as "the intrinsic ability of a system or organization to adjust its functioning prior to, during, or following changes, disturbances, and opportunities so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel, et al., 2015). So at the heart of Resilience Engineering is the idea of adaptation, because complex sociotechnical systems are underspecified and not wholly predictable so adaptation is necessary for successful performance. Resilience Engineering therefore concerns itself with studying how this adaptive capacity operates, and how it can be supported in practice. Resilience Engineering proposes that rather than reducing adverse events per se we should be enhancing resilience abilities of the system to succeed under varying conditions, e.g. focus on how the system monitors, anticipates, responds, and learns (Hollnagel, 2011).

Safety-II has its roots in Resilience Engineering, and it might be argued that the two are synonymous. However, with the relabelling comes a contrast with Safety-I, which might be an oversimplification but is still useful (Lawton, 2018; Sujan et al., 2019a). Safety-I is defined as a 'find and fix' approach to safety that tries to resolve problems to ensure the poor outcomes do not happen or never happen again (Hollnagel, et al., 2015). At its simplest these problems are conceptualised as single component failures, sometimes called the root cause. However, in practice, many safety projects are configured to focus on reducing risk so it is 'as low as reasonably practicable' (ALARP), which can involve addressing multiple vulnerabilities. Safety-II's mantra tries to turn this on its head, so rather than preventing as many things as possible from going wrong, we try to make as many things as possible go right (Hollnagel, et al., 2015). Importantly, this expands the scope of concern for safety, i.e. we attend how safety is maintained and created in 'normal' performance and when things go well. This turn to everyday safety also means to better understand work-as-done (WAD) that engages with what people 'actually' do in practice given goal conflicts and contradictions, in contrast to work-as-imagined (WAI) that engages more with what people 'should' do from a more idealised perspective that can neglect the messiness of practice (Hollnagel, et al., 2015).

FRAM (Functional Resonance Analysis Method) (Hollnagel, 2012) is the best known method associated with Resilience Engineering and Safety-II. Its purpose is to examine the performance variability of complex sociotechnical systems to better understand WAD. It decomposes the system into functions, to move away from 'what a system is' to 'what it does'. Each function is examined for its potential performance variability, then interactions between functions are examined. 'Functional resonance' is used to describe how outcomes can 'emerge' from everyday variability of many functions, to move away from simple notions of 'cause and effect'. FRAM is built on four principles (Hollnagel, 2012):

- The principle of equivalence of success and failure – Success and failure come from the same source, i.e. they are not fundamentally different in nature. Approximate adjustments mean that people adapt successful most of the time but sometimes variability in performance will lead to unsatisfactory outcomes.
- The principle of approximate adjustments – Due to limitations in resource, uncertainties, underspecified systems and variance demands people will adjust to suit the situation. This gives rise to performance variability which is inevitable, ubiquitous and necessary.

- The principle of emergence – Complex systems with many links and fluctuating approximate adjustments become intractable as it is impossible to predict what will happen precisely beyond expecting regular events.
- The principle of functional resonance – Functions represent the different things a system does. Due to approximate adjustments these will exhibit performance variability. Functional resonance refers to how functions may impact each other's performance variability. Small changes could lead to disproportionally large effects and vice versa.

FRAM's history shows that it continues to evolve. It was first proposed as the Functional Resonance Accident Model (Hollnagel, 2004) which was focused on how functions can amplify and resonate to spiral out of control. FRAM (Hollnagel, 2012) was reborn into the Functional Resonance Analysis Method, which proposes to examine and manage both wanted and unwanted forms of performance variability. This is more in keeping with Safety II's concern for both positive and negative outcomes. There are different styles of FRAM study. Many studies, particularly the early ones, focus on understanding the complex functional interactions that led to something bad happening or unwanted variability that could lead to something bad happening, e.g. studies looking at near miss and accident analyses (e.g. Nouvel, et al., 2007; Hollnagel et al. 2008; Herrera & Woltjer 2010; De Carvalho 2011), risk and safety assessments (e.g. Lundblad et al. 2008; Woltjer & Hollnagel 2008; Belmonte et al. 2011; Pereira 2013), and hazard analyses (e.g. Frost & Mo 2014). In contrast, Furniss et al. (2016) perform a different style of FRAM looking at how functions can positively resonate to understand whether a sociotechnical system will flourish or stall, beyond the concerns of safety. Many modern studies using FRAM take a more neutral approach to performance variability, which try to understand its presence, nature and how to manage it, e.g. to assess vulnerabilities and opportunities between opponents in an adversarial war game (Woltjer et al., 2009); to analyse why fluoride varnish is not applied by dentists and to design a complex intervention to address this (Ross et al., 2018); to support hospital work (Hounsgaard, 2016); and to understand why blood sampling varies (Pickup et al., 2017).

In the current paper we explore a non-normative approach to FRAM, so rather than focusing on dampening unwanted variability or amplifying positive variability per se we take sources of performance variability as a starting point to understand and describe underlying systems contradictions (Sujan et al., 2002; Sujan et al., 2015). The notion of contradictions is rooted in cultural-historic activity theory (Cole, 1998). Systems contradictions present people with margins of manoeuvre that need to be effectively managed, e.g. due to conflicting rules and advice, goal conflicts, trade-offs and mismatches between demand and capacity and mismatches between competences and situational issues.

3 Method

3.1 Setting

The ICU is part of a teaching hospital in the Midlands in England. The unit has 20 beds. There is generally one nurse per patient, and doctors are routinely present. The unit uses paper prescription charts and smart infusion pumps that are programmed with the rate, time and dose. The smart pumps contain a drug library with hard and soft limits. An Electronic Health Record (EHR) is used to record drug administration volumes and review patient records. The double checking of drug administration by two nurses is recorded by signatures on paper. The ICU has invested in some ready to administer infusions that can be immediately administered to the patient (e.g. fentanyl, insulin, noradrenaline and adrenaline) and ready to use infusions (e.g. glyceryl trinitrate, midazolam

and morphine) which just require to be drawn up into a syringe. The remainder must be made up on the ward.

3.2 Ethics and project context

The work was undertaken as service improvement and had received local approvals from the hospital R&D department. All authors of the paper were both participants and investigators on the project, so no research subjects were recruited and consent was not required. Members of the ICU team wanted to better understand how automated and autonomous technologies could help with intravenous infusion administration on the ward. Specialists in safety assurance, NHS IT and human factors were part of the project team and the project advisory board. The study involved co-designing research questions, joint sensemaking and was collaborative in nature (Zamenopoulos, & Alexiou, 2018)

3.3 Data collection

A series of meetings and workshops were held roughly on a monthly basis between September 2018 – May 2019, supported by emails and communications between, to share ideas and understand more about intravenous infusion administration on the unit. Clinical input to the workshops was provided by the clinicians on the project team who were also practicing members of staff at the ICU with backgrounds in intensive care nursing, pharmacy and anaesthesia. The initial familiarisation period included two process walks as well as in-depth demonstrations of the infusion pumps and IT systems by the clinical team members to the non-clinical team members. The FRAM analysis was facilitated by DF and MS, who are both experienced with the methodology. Data were recorded in graphical format using the FRAM Model Visualiser (Hollnagel & Hill, 2016), in tabular format (for analysing functions), and in detailed free-text notes. The analysis was complemented by experiences from a previous project DF was involved with that investigated intravenous infusion administration practices and errors in England (e.g. Blandford et al., 2016; Lyons et al., 2018; Furniss et al., 2019a).

3.4 FRAM analysis

Functions were identified and mapped in a FRAM network diagram to develop the generic FRAM model for intravenous infusion administration. Each function has six aspects (see Figure 1), whereby the output of one function can influence the variability of another function's aspect – this forms the basis of how the variability of many functions can lead to resonance. Reflecting on each function's aspects can identify more functions and functional links. To help make sense of this functional network colours were used to group the functions into different areas of functional activity, links between functions were also used to specify the main relationships even though these could vary depending on different instantiations of this model.

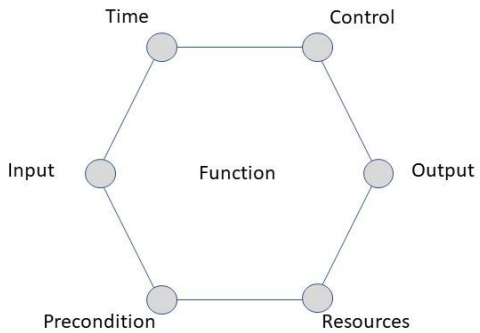

Figure 1: FRAM node with six aspects

The generic FRAM model and insights into performance variability were developed iteratively alongside the generation of questions , data gathering and analysis. We described the main sources of performance variability and where this was high developed a tabular analysis to investigate. Resilience abilities (Hollnagel, 2011) were also brought into this analysis where relevant to try to identify more abstract markers of resilience:

- Adaptation – knowing what to do in the face of disturbances, issues and opportunities;
- Monitor – knowing what to look for and monitor which might impact performance;
- Learn – to be able to learn the right lessons from the right experiences; and
- Anticipate – be able to anticipate issues and opportunities in the future.

The analysis focused on tensions and contradictions that could be a source of dynamic trade-offs that need to be negotiated for safety (e.g. Sujan et al., 2015). It also included uncertain performance conditions, where the next course of action might be unclear. For example, this could include a mismatch between resource and situational demand, conflicting procedural advice and competing system goals, and a mismatch between competence and situational demands.

The analysis excluded the usual failure modes associated with SHERPA (Embrey, 1986) and FMEA (Stamatis, 2003) (e.g. right action on wrong object, action omitted, etc.). It could be argued that these failures are just part of everyday performance variability, but they come with a negative and normative connotation (i.e. the "failure" in failure modes is a negative). We wanted to look at performance variability as something inevitable and potentially useful. That is why we focused our analysis on contradictions and goal conflicts inherent in the system, and how they are managed for everyday safety. From this perspective traditional failure modes could be a distraction, leading back to hackneyed ways of 'find and fix' thinking. Failure modes are important, and form part of the whole picture of performance variability, but they were intentionally not a focus of our analysis.

4 Results

4.1 FRAM: Generic model of intravenous infusion practice

Our FRAM model includes 38 separate functions (Figure 2). Figure 2 shows seven different areas of functional activity including medication ordering (green nodes); preparing the intravenous infusion (blue nodes); interacting with the patient (grey nodes); administering the infusion (red nodes); double checking of the preparation and administration (yellow node); monitoring and documentation of the administration (purple nodes). Three miscellaneous activities: other things the nurse is doing, other things the doctor is doing, and other things the patient are doing are not shown in Figure 2 – this is due to their non-specific influence on many functions. Figure 2 has a 'modern' rendering using the FRAM Model Visualiser (Hollnagel & Hill, 2016) so background functions, which only provide input to foreground functions, are not displayed as hexagons. This does not mean they are not influential. Background functions are meant to be part of the context rather than the system, but for reading Figure 2 this division can be considered fairly arbitrary. The references in boxes, e.g. 1.A. and 2.C., are cross-references for variability described in Tables 1-3.

4.2 Description of performance variability for our ICU setting

The following section describes the variability in and around intravenous infusion administration, which relate to the seven areas of functional activity identified in Figure 2.

4.2.1 Medication Order

Four functions relating to medication order were recognised in Figure 2. To order medication ideally there should always be a specific and comprehensive written prescription for nurses to work against

to ensure they get the administration right. However, this is not always possible, for example in urgent cases where a verbal order may be given. Table 1 details this and other forms of variability that occur in the prescribing and medication order process.

The medication order varies in important ways. There could be an order for a new drug, there may be an order to continue a drug a patient is already receiving, or an order to change the details of administration e.g. rate, dose, etc. The order could be for a one-off dose, a continuous infusion or an infusion that needs to be titrated to patient need. The order might be for immediate administration or it might stretch over hours and days.

One of the most interesting sources of variability for ordering medication is whether it is written or verbal, as this can have a large impact on the process downstream. The benefit of introducing this performance variability (i.e. written or verbal) is that it can deal with different kinds of demands, e.g. a verbal order is very good when there is an urgent need for treating the patient and conversely a written order provides a clear audit trail and details for nurses to act upon. Verbal orders tend to be in the presence of the doctor, e.g. during admission or when the doctor is treating the patient like putting a central line in or giving life support. After the admission or treatment is complete the doctor will often sit down and do the paperwork including the prescription. The other main way is for the nurse to anticipate or respond to what the patient needs before the doctor and prompt the doctor for this who can then review and write it up later. To help try to mitigate the risk of error two nurses should hear the order if it is a high-risk medication, if it is a low risk medication then this is not warranted. Nurses will document the medication administration in their notes, so it is recorded somewhere even in the absence of a written prescription.

The order may be initiated by the nurse, by the doctor, or discussed jointly. This is an interesting source of variability because it has implications for control and sensemaking. Ideally both the nurse and the doctor will have a coherent view of the patient, e.g. what is wrong with them, what needs to be done, their trajectory and some *anticipation* about what issues may arise. Medication orders should be understood and fit this picture. If a medication order does not fit this picture then there should be a sense of unease and a need to question further. For example, a nurse might challenge a doctor about an unusual prescription. Similarly, if a nurse is monitoring a patient who needs medication for some reason they can suggest this to a doctor and if the request is coherent with the doctor's view of the patient and what the nurse is telling them then they could approve it.

4.2.2 Preparation of medication administration

Nine functions relating to medication administration were recognised in Figure 2. This ICU has invested in pre-prepared medication for high risk infusions so the nurses do not need to make it up on the ward. This saves the nurses time in preparing medication and adds control for variability that could occur during the preparation process, i.e. so what is inside bags and syringes is consistent because it is made in pharmacy away from the ward. This greatly simplifies the medication preparation process because the nurse merely has to collect the right medication and the equipment needed to administer the infusion, e.g. a giving set, a label for the giving set, etc. This stage in the process, due to the pre-pared medications, has a lower potential for performance variability. However, it is still critical that the right medication and dose are selected.

Figure 2: FRAM network diagram of intravenous infusion administration [Green nodes: medication order; Blue nodes: preparation; Red nodes: administration; Yellow node: double checking; Purple nodes: monitoring and documentation; Grey nodes: patient interaction]. The references in boxes, e.g. 1.A. and 2.C., are cross-references for variability described in Tables 1-3.

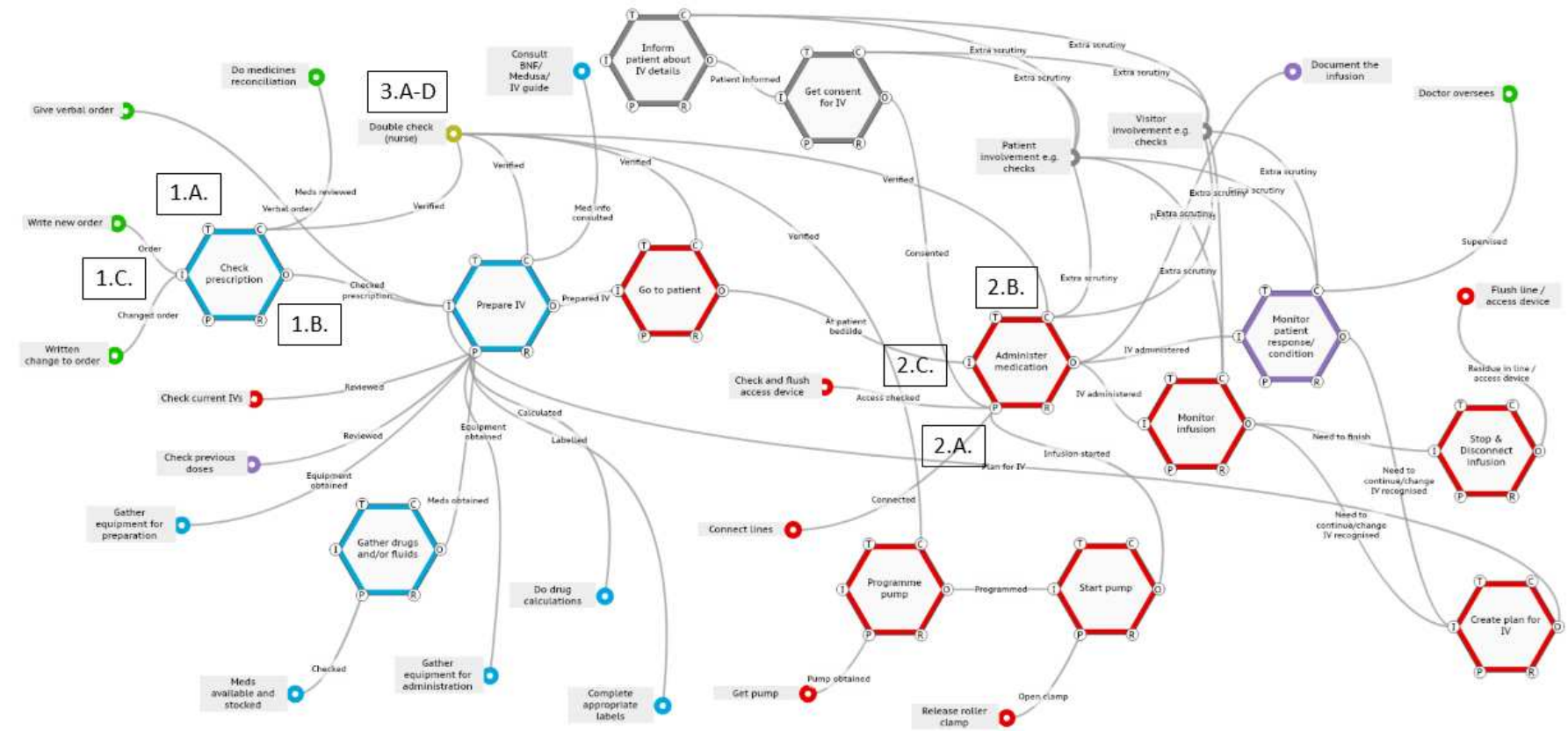

Table 1: Medication Order variability (*resilience abilities in italics*)

Manifestation of variability: what was observed?	Contradictions and uncertain performance conditions: how does this demonstrate resilience?	Further notes and wider system activity: what other upstream/downstream links does this variability have?	Reference in Figure 2
There could be a written prescription or a verbal order for a drug.	There might be an emergency scenario whereby the drug has to be given immediately, or doctors may be too busy to write an order so advise that the administration proceed without it (*adaptation*).	In all cases a written order should follow a verbal order. This creates an extra function for the nurse and doctor to *monitor* that a written order follows.	1.A.
The prescription/order could come before or after the administration.	Nurses may perceive a need for fluids or drugs but the doctors might not have written an order yet. For example, a continuous infusion might need to be officially reordered when the current infusion is ending but the doctors might be unavailable, so the nurse continues it in *anticipation* of an order.	Again, this creates an extra function for the nurse to *monitor* that they follow this up with the doctors and an order follows.	1.B.
The prescription/order could be very specific and comprehensive about rate, dose, etc.; it could also be more general like ordering 'fluids', or incomplete.	What details are missing, how they are perceived and the demands of the context will impact the *adaptive* strategies chosen: If these are perceived as important then the doctor should be challenged. If not perceived as important the nurse will most likely get on with it, and add and/or correct details later if necessary. The urgency of the drug, its potency, and the availability of the doctor might also influence how individuals adapt. There is a trade-off between being efficient (getting on with the task) or being thorough (making sure all information is complete and correct).	Challenging the doctor depends on perceived consequences (e.g. how uneasy the nurse feels about the missing information), and the availability of the doctor (e.g. if they are present or the next bed along the cost is low, if they are away from the ward they could be hard to find and might not like being interrupted).	1.C.

4.2.3 Patient and visitor interaction

Four functions relating to patient and visitor interaction were recognised in Figure 2. Many patients are sedated and not awake in ICU and so the potential involvement of patients and visitors in medication administration is low compared to general wards. If the patient is awake and well enough they will be asked to confirm their details, and be asked about their allergies. However, this

interaction is handled on a case by case basis (*adaptation*). Nurses generally will only look after one very sick patient, and not 7-12 patients on a more general ward, so there is less likelihood they will get patients and their details confused, i.e. there is lower variability here.

4.2.4 Medication administration

Thirteen functions relating to medication administration were recognised in Figure 2. Generally, the nurse will proceed with hanging the bag or putting the syringe in the pump, programming the pump, setting up a line, checking the access point, flushing it, connecting the line and then starting the pump. The nurse will monitor the infusion to check there are no blockages and that it is proceeding as expected.

An interesting source of variability in this section, which needs to be managed, and is different to other non-critical care contexts, is managing the throughput of the intravenous infusion medications. Critical care patients may need many infusions and today's technology means that patient can be on 10-20 infusions at one time. When patients are this sick there may be two nurses looking after the one patient. The management of these infusions, including the different priorities, titrations, timings, different lines and access points can be challenging. For example a patient might have a limited number of operational lines, already have the majority of them being used, then be prescribed more infusions some which are short, some longer but more urgent and others that should be given at certain times (e.g. an antibiotic that needs to be administered every six hours). These might not always be compatible either.

This prioritisation of medications is constantly evaluated as new medications are added and the patient condition changes, e.g. there might be a spike in blood sugar levels which suddenly means that administering insulin becomes more important and urgent then it had been before. If in doubt about what to prioritise nurses can speak to doctors or senior colleagues. Variability associated with medication administration is captured in Table 2.

Table 2: Medication administration variability (*resilience abilities in italics*)

Manifestation of variability: what was observed?	Contradictions and uncertain performance conditions: how does this demonstrate resilience?	Further notes and wider system activity: what other upstream/downstream links does this variability have?	Reference in Figure 2
Drug administration is planned depending on priority or 'pecking order'.	There may be many drugs prescribed for the patient, and the patient may be limited by the amount they can take concurrently when considering access points and incompatible drugs cannot go down the same access points. The nurse will administer drugs as best they can, e.g. doing short infusions first and prioritising more critical drugs (*adaptive strategy*).	Nurses will *learn* strategies to deliver infusions timely and effectively.	2.A.
Drug is infused through faster than 'normal'.	As above, but rather than infusing drugs at normal speed they may be infused faster, with consideration to the impact of this, to make room	Nurses will *learn* strategies to deliver infusions timely and effectively.	2.B.

	for other infusions (*adaptive strategy*).		
The access site might be used despite it being in poor condition	Nurses should check intravenous infusion access points are good before use. However, it might be that delaying urgent drugs is worse then using a poor access point, so it will be used (*adapting*).	This trade-off could lead to infection issues that need further intervention, but administering vital medication may take priority.	2.C.

4.2.5 Double checking

One double checking function, which had multiple links, was recognised in Figure 2. Double checking by a registered nurse should take place once when the drugs have been gathered but before the infusion is set-up and started to ensure that the prescription, preparation and administration of the infusion are performed on the correct patient as expected.

However, as above, we find that variability is inevitable given the uncertainties and contradictions that are inherent in the system, e.g. there are competing policies and priorities around not leaving your patient and needing to leave them to double check someone else's infusion. So variability serves a good reason, to try to satisfy competing goals and to reduce interruption to work. The main source of variability is a tension between fulfilling concurrent activities across different members of staff who are meant to be involved in the check, and the subjective risk assessment of those staff to determine what sort of check would be satisfactory. See Table 3 for double checking variability.

Table 3: Double Checking variability (*resilience abilities in italics*)

Manifestation of variability: what was observed?	Contradictions and uncertain performance conditions: how does this demonstrate resilience?	Further notes and wider system activity: what other upstream/downstream links does this variability have?	Reference in Figure 2
Double checking is not always done.	There is a trade-off in other operational demands of the ICU and the perceived risks of the medication administration (*adaptation/anticipation*).	Many activities are happening concurrently in ICU, so there is a cost and inconvenience in interrupting these other activities.	3.A.
The thoroughness of the check can vary, e.g. just a confirmation versus a more independent check.	The double check is often done together rather than being an independent check. This is perceived to save time and effort. A full independent check does not naturally fit with the working patterns of the nurses (*adaptation*).	Doing the double check together can allow for discussion and wider *monitoring* activities between staff, e.g. how the member of staff is doing and checking the situation of the patient.	3.B.
What is actually checked can vary. This can manifest at different levels. At a higher level is the prescription, preparation, administration, patient, and infusion	Again there is a trade-off in other demands and the perceived risks of the medication administration. For example, someone who is training to do intravenous administration of a high risk drug would have a thorough check – indeed this training	Basic training seems a special case, but there are a whole host of shades of experience between this and highly experienced nurses where they can *learn* from each other beyond checking items but being involved in overseeing activities and care	3.C.

pump all checked? At finer grained level are the rate, volume, time, previous infusion, current incompatible medication, the insertion site and allergies checked?	scenario might be one of the main occasions where everything is checked methodically. In contrast, an experienced nurse giving a low risk drug might receive a short confirmatory check more to fulfil the requirement that some check has taken place rather than any real interrogation of what is happening (*adaptation/anticipation*).	for patients. For example, experienced nurses might want reassurance if they are dealing with a drug they are not used to. Depending on the situation nurses might focus on items they think are critical to check (*anticipation*).	
The timing of the check can vary, e.g. before or after the administration.	The more unease about an administration there is the more staff will wait for a double check before proceeding. Staff may proceed with the administration if it is low risk, urgent and other staff are unavailable for a double check. Staff may seek a double check after administration for enhanced *monitoring*.	Many tasks are planned and proceed concurrently between busy individuals. There is a negotiation between perceived risks and priorities, as well as allowing flexibility for tasks to maintain a flow that is not too disruptive.	3.D.

There are different 'push' and 'pull' factors involved in the subjective risk assessment by staff. If the person who is meant to be doing the check feels uneasy about the infusion, e.g. the member of staff may be new, they may be busy and appear stressed, it might be a high-risk drug, the patient might be particularly poorly, etc. they might 'push' a more thorough check on to the process. If the nurse who is meant to be receiving the check feels uneasy, for similar reasons to that outlined above, then they might 'pull' or invite a more thorough check. The workload of both members of staff and the criticality of interrupting their activities will also interact with the thoroughness of the check and when and where it is done. Double checking might also be affected by the team culture (e.g. tension could be caused if someone is doing them pedantically and the team is not doing them thoroughly).

4.2.6 Monitoring and documentation

Three functions relating to monitoring and documentation were recognised in Figure 2. Once the nurse has set up the infusion they should document what they have done, monitor the infusion and the patient's response to the infusion. The nurse reported that they would continuously monitor for alerts and alarms, react accordingly and do hourly checks. They reported that the design of the medication chart is not good, which might mean more mistakes and omissions, but these should be picked up during ward rounds and shift handovers.

The patient is first seen by the admitting doctor and should be seen by a consultant within 12 hours. This can depend on doctor's workload and priorities. Time pressure may mean not all patients are seen; and some patients may have a more detailed review compared to others depending on need. The patient will have a full review once per day, and be seen on the ward round by the entire team. There is often a second less formal ward round. The ward round might focus on more interesting and important details. Other jobs might lead to the ward round being rushed.

A handover sheet is prepared for shift handover, from day to night, etc. There are independent handovers between nurses, and separate handovers between doctors, so no multidisciplinary handover and they come together during ward rounds. The shift handover operates as a safety check as the patient's prescription chart, infusions and results will be reviewed.

4.2.7 Broader system activities

Three functions relating to broader system activities on ICU were recognised in Figure 2. Intravenous infusion administration takes place within a broader set of activities, some of which are predictable and others less so. For example, nurses may be busy with other patients if they need to look after more than one patient, they might be drawn away by an emergency, to get something or need to be on a break. Floating nurses may provide the extra capacity for extended periods away, e.g. a break, and adjacent nurses might be able to cover temporarily, e.g. if a nurse has to get something.

Doctors are normally more available on ICU compared to general wards because of the state of the patients and the shorter time scales in which things can develop and decisions need to be made. However, doctors may be busy or unavailable for a multitude of reasons, e.g. called away for emergency support of a patient on a different ward.

There might also be other demands on the patient that can disturb plans and infusion administration, e.g. the patient may need to be bathed, or they might be rushed off to have a CT scan where all infusions are disconnected (except the most critical ones, e.g. to keep them unconscious). These pressures will impact how the functions, tasks and activities are coordinated.

5 Discussion

We wanted to explore what inherent contradictions there are in the system and how they are managed for everyday safety, which seemed more conducive to Resilience Engineering thinking than looking at error occurrence and recovery. Following this, a defining feature of our FRAM analysis has been its non-normative approach to understanding systems contradictions, which fits with those FRAM studies that take a more neutral approach to performance variability (e.g. Pickup et al., 2017; Ross et al., 2018). We intentionally excluded failure modes from our analysis, not because they are not important, but because we did not propose that type of analysis. To situate this use of FRAM, we believe it is useful to distinguish these different styles of use:

- Potential failures, e.g. error occurrence and recovery;
- Positive resonance and systems that excel;
- Wanted and unwanted variability; and
- Inherent contradictions and underlying goal conflicts.

Of course, a comprehensive analysis might focus on all four. However, there are risks in combined approaches that one style will dominate another. For example, it might be easy to pre-judge that a cursory double check is unwanted, when actually this has performance gains for other parts of the system. This is why our non-normative approach suspended these judgements so these underlying contradictions and their rationale could be explored further.

This paper helps develop the picture of performance variability around intravenous infusion medication administration. Kaya et al. (2019) present a FRAM network with similar functions to those presented in this paper. However, they focus more on the preparation stage whereas our unit had many pre-made drugs so this was less variable. They also do not emphasise the high degree of variability found around verbal orders, double checks and tube management that we found in our study. Schutijser et al. (2019) focus on how nurses adjust the double check during injectable

medication administration. Furniss et al. (2018) describe some of the variability in double checking procedures and practices between hospitals in England, which include doing single checks for some drugs, different degrees of independent check, and checks covering different parts of the administration process. Our study suggests the nurse's risk and situational assessment is key in determining what type of double check is satisfactory. Schutijser et al. (2019) highlight practices like a digital double check which were not available in our ICU setting because their practice is paper-based, but they do not discuss much the thoroughness of the double check (e.g. whether it is fully independent or more of a confirmatory check that is done together with the two nurses), the factors involved in whether a nurse might invite a more thorough double check or whether the checking nurse might push for a more thorough double check, which were features of our study. Differences between similar studies are to be expected 1) due to the actual variability between settings, and 2) due to variability between analyses especially where systems are complex and nuances can be hard to handle.

Furniss et al. (2019) proposed that complex sociotechnical interactions need to be examined to understand how everyday performance variability emerges, e.g. between structure and agency. In this paper we have seen how contradictions between structures can create margins of manoeuvre that need to be negotiated for safety. An example of a tension is when a nurse is instructed to give a list of medicines that the patient cannot receive all at once, so they need to prioritise what to give first (e.g. Oduyale et al., 2020). So, the tensions or contradiction is built into the objective (or goal) of the function <administer medications>, because the patient should get all required medications, but they cannot all be given at the same time. An example of a tension between activities is the double-checking function. Considered by itself and isolation, this function should happen all the time, i.e. should have 100% reliability. However, as there are other activities and competing goals and priorities, nurses use their subjective assessment of the context and the risks involved in a particular situation to resolve this tension through a dynamic trade-off (see ETTO Hollnagel, 2009).

The normal advice in how to manage performance variability after doing a FRAM study is to try to find ways to dampen unwanted variability and enhance wanted variability (Hollnagel, 2012). However, having taken a non-normative approach we have not judged what is wanted and unwanted variability, instead variability is merely inherent in the system and has benefits, but can also contribute, at times, to unwanted outcomes. Pertinent to the wider context of our project is that we do not want to introduce new technologies that might design out the adaptive capacity to cope with variability. For example, we have seen that some medication can be administered before a prescription is written – work-as-imagined (WAI) would dictate that this should not happen. A naïve design might focus on WAI and not allow drug administration before a formal written prescription, which could be disastrous in urgent cases. Examining the potential enhancement and disruption to the management of performance variability, caused by new technology, is part of future work. For example, this could include bar code administration systems that might unduly straight jacket adaptive behaviour and smart e-prescribing systems that can automatically detect drug conflicts with known allergies and other drugs being administered.

In terms of building the adaptive capacity of the current system we can seek ways to enhance how people handle this variability, through supporting internal structural changes, e.g. support people to recognise and develop strategies for making trade-offs, how to prioritise, and to know when to recognise they need to ask for help. Staff learn these strategies informally on the job, but they are rarely made explicit. Indeed, there may be some discomfort in admitting the complexity, risky and degraded nature of work and the workarounds that must follow, e.g. giving drugs before a prescription and using infected sites showing an early sign of infection prior to replacement to

administer drugs. Even formalising a pecking order to drugs that should be given before or after one another may be problematic because of the contextual nature of the decision, e.g. a non-critical drug may be given before a critical drug if it is quick so it is not unduly delayed. A first step in enhancing the adaptive capacity of individuals might merely be to recognise their expertise, get them to reflect and share their repertoire of resilience strategies (Furniss et al., 2011), so they can be discussed, monitored and others can learn about them. Developing communities of practice and storytelling might help distribute this knowledge. Where sources of performance variability cannot be resolved then adaptive capacity should be enhanced.

External structural design changes can also help and hinder the performance of the system. The system has already evolved to the state is in today through organisational and purchasing decisions, e.g. choosing the infusion pumps the ICU uses and deciding to invest in pre-made drugs. This already influences sources of performance variability. Future organisational and design decisions need to consider the potential impact of new interventions to ensure that they manage performance variability in the right way, and reduce the chance of unintended consequences. For example, FRAM has been proposed to project forward to consider future designs and interventions to assess their effectiveness and suitability (Ross et al., 2018; Ferrerira & Cañas, 2019).

Part of the limitations of this study is that it was only conducted in one ICU, comparing its practices with other ICUs would have been interesting. A strength of this study is that it involved different disciplines from ICU, albeit the nurse on the project team was the clinician most closely involved in the analysis. This is justified as nurses have the most involvement in the medication administration process. However, a larger group of people could have been engaged with for data gathering and validation. This work is part of a wider ongoing project looking at the potential for technological interventions on the ICU, so direct interventions resulting from this FRAM study were not built in to the programme of work. Again, this would be an interesting area of future research.

6 Conclusions

We have applied FRAM to explore what inherent contradictions there are in the system and how these are managed through performance variability and dynamic trade-offs to create safety on a daily basis. Three main areas of high performance variability are highlighted: medication order, medication administration and double checking. We have taken a non-normative approach that moves away from issues of compliance, and wanted and unwanted performance variability. Consequently, this also looks towards different remedial actions, i.e. rather than reducing risk and error per se we want to build adaptive capacity to cope with these inherent contradictions in a satisfactory way. These contradictions can be seen as sources of tension between different internal and external structures in the system, which invite the agency of individuals to work out how they are going to handle these tensions.

Funding

[Blind for review]

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