Tracheostomy Transfers: A Case Study in the Application of Formal Methods to Intra-hospital Patient Transfers

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Tracheostomy transfers: A case study in the application of formal methods to intra-hospital patient transfers

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***Abstract*—We review a generic framework for rigorous workflow modelling and verification that was recently applied to healthcare collaboration patterns, and we show how it can be utilised to help both medical staff and health informaticians build a systematic understanding of informal practices followed during intra-hospital patient transfers. A case study is discussed, demonstrating how the logical foundations of our approach help capture and enforce significant aspects of intra-hospital transfers that are pertinent to their improvement.**

***Keywords*—Healthcare workflows, process model, formal methods, intra-hospital transfers, tracheostomy.**

I. Introduction

In CBMS 2012 we presented a rigorous, computer-based approach to the modelling and verification of collaborative patterns in healthcare teams [1]. More specifically, we discussed existing pen-and-paper specifications of healthcare collaboration patterns, which we mapped to a logical, process-based formalism. Using a diagrammatically-driven, theorem-proving based approach, we developed an interactive means of constructing formally verified workflows that guarantee the correctness of the information flow between processes specified by the healthcare patterns.

The importance of such workflow models for developing efficient, integrated care pathways has been highlighted in numerous recent studies [2]. In addition, a close collaboration with clinicians during the modelling stage has been identified as crucial in order to provide a tailored and viable solution.

In the current work, we adopt these principles by taking our approach further and employing our framework to model and verify informal practices followed during intra-hospital transfers of tracheostomy patients at St Marys Hospital, London. In particular, we formally model the typical but ad-hoc processes involved in such transfers, making sure that the resources and information needed are explicitly represented and that exceptions are incorporated. The tracheostomy transfer processes are then rigorously composed to form a well-defined workflow for the entire transfer lifecycle, thus providing us with a visual representation of the transfer flow that is backed up by mathematical proofs. The resulting formal and verified model of previously ad-hoc transfer procedures can help healthcare practitioners understand and potentially improve many aspects, including safety-critical ones, of intra-hospital transfers.

The paper is organised as follows: In Section II, we provide a brief overview of our workflow composition framework and its previous application to the modelling and verification of healthcare collaboration patterns. We also describe significant and challenging aspects of current intra-hospital transfer practices, which call for a clear and systematic solution. In Section III, we present the employment of our approach for a real-world example of intra-hospital transfers. The data collection and modelling lifecycle is discussed in Section III-A, the workflow composition is presented in Section III-B, and the benefits of our approach are clarified with respect to the intra-hospital transfer issues identified in Section II. Finally, we discuss related work in in the area of workflow technologies in Section IV, we summarise our future plans on how to extend our approach to enforce clinical guidelines in new healthcare domains in Section V and we conclude in Section VI.

II. Background

We briefly describe our framework for the formal construction and verification of workflows, and review its recent application to the modelling of collaborative work in healthcare. We then mention a few aspects of current intra-hospital transfer procedures that are pertinent to patients' safety.

A. A Brief Overview of our Framework

In previous work we devised a formal framework for process modelling and composition [3], which is supported by a visual tool with incorporated theorem proving capabilities [4]. The logical foundations of our framework lie in the use of Classic Linear Logic (CLL) and the proofs-as-processes paradigm [5], which we embed within the modern proof assistant HOL Light [6]. In this, processes are specified as CLL statements, along with their single, composite or optional inputs and outputs. Composition is achieved by proving the expected, composed workflow as a conjecture, making it possible to combine individual processes in a sequential, parallel or optional fashion. In order to facilitate this procedure, we defined proof commands within HOL Light that correspond to high level workflow composition actions. This way each action is enabled by a custom, fully-automated proof command that applies a number of CLL inference steps in order to generate the verified result at the logical level, thereby ensuring the action's correctness. Apart from providing guarantees of soundness for the composition, this approach allows for systematic resource accounting and explicit exception handling, while making it possible to enforce desired policies.

The graphical user interface of our framework makes it considerably easier to use for people who are not familiar with formal methods, logic or theorem proving. Domain experts can, thus, specify processes and compose them purely visually, while all the reasoning and logical checks happen seamlessly in the background. This way, the output model has a two-fold representation: an intuitive, visual representation, where processes are depicted as rectangular nodes with edges that correspond to their inputs and outputs, and a fully-rigorous, underlying logical representation, where the process composition is described by a CLL proof.

More recently, we accomplished the automatic translation of formally specified workflows into executable Scala code [7]. The user can, thus, obtain an executable, concurrent version of the formally verified workflow at the push of a button, hence propagating the logically enforced policies. This automatic deployment solution is particularly valuable in highly dynamic environments as it allows any changes made in the original process model to be easily propagated to the software system.

B. Rigorous Process-Based Modelling of Healthcare Collaboration Patterns

In our CBMS 2012 paper, we described how our rigorous framework can clarify the accountability and responsibility of staff members in collaborative healthcare work [1]. In particular, we examined pen-and-paper specifications of two healthcare collaboration patterns – the assignment and the delegation of a service to a member of staff – that were originally proposed by Grando et al. [8]. We represented the keystones as processes, which were then composed into workflows to match the assignment and delegation patterns. By explicitly representing the desirable safety principles of the patterns and by exploiting the logical basis of our approach, we enforced and verified the responsibility and accountability properties of each pattern. Moreover, we extracted an executable model of each pattern composition as a process calculus term, which enabled the verification of concurrency properties.

C. Intra-Hospital Patient Transfers

Intra-hospital patient transfers (IHTs) are a common aspect of hospital care, and they are inevitable for critically ill patients in the emergency department [9]. They are also hazardous [10], with the occurrence of adverse events reaching levels of 68% [11]. The most important factor contributing to the safety problems of IHTs in the UK is the fact that most intra-hospital transfer procedures do not have well-defined, succinctly specified guidelines [12]. Medical staff are faced with either an abundance of long and complicated policies, such as the 40 page long *Guidelines for the transport of critically ill adults* [13] by the Intensive Care Society (UK) or with a complete absence of relevant documentation. A guideline practice gap is apparent [14], leading medical staff to employ informal, mostly oral-based means in order to support the transfers. Such ad-hoc procedures are prone to errors, omissions and miscommunication, thereby posing an increased risk to patients' safety [15] and causing avoidable problems, such as delays and unnecessary use of resources [16].

In order to address these issues one needs to have a solid understanding of employed IHT practices. However, developing a clear model of IHTs is a non-trivial task, especially given their complex nature, the high degree of interaction between members of staff from different departments, and the variety of resources involved. In this paper we argue that our approach can effectively undertake this modelling task and explicitly address typical IHT issues. We support our claim by applying it to a real-world transfer procedure, which we describe next.

III. Rigorous Modelling and Verification of Tracheostomy Patients' Transfers

Health practitioners at St Mary's Hospital, London, have long identified that there is a lack of well-defined guidelines for intra-hospital transfers, which may lead to errors and delays. As part of an ongoing collaboration, we settled on applying our framework to a specific and typical case of intra-hospital transfers there, so as to clarify the practices followed locally. We, thus, focused our study on intra-hospital patients' transfers for tracheostomy, which is a common procedure that requires the transport of patients from the ICU to the operating theatre. Through close collaboration with hospital staff, we specified and rigorously composed the tracheostomy transfer processes to form a well-defined workflow. This section details our methodology, the output models and the benefits obtained.

A. Modelling Tracheostomy Transfers as Processes

The data for modelling the tracheostomy transfers at St Mary's Hospital was collected over a period of three months using a variety of methods. A consultant anaesthetist was shadowed during her shift as the operating theatre coordinator, making it possible for us to have a hands-on experience of intra-hospital transfers. Contextual interviews [17] were carried out with a range of stakeholders that included nurses, doctors and porters, thus allowing us to consider a range of viewpoints and observations when modelling the tracheostomy transfers. Furthermore, two extensive interview sessions were carried out with three anaesthetists, which enabled us to examine tracheostomy transfers in more depth. Finally, the medics provided us with data, in the form of notes and hand-sketched flowcharts that aimed to capture the main aspects of tracheostomy transfers.

The focus of data collection was to highlight safety-critical aspects of intra-hospital transfers at St Mary's Hospital. We, thus, gathered information about typical IHT tasks, resources involved, communication needed and exceptions that may occur. These aspects were considered for three IHT stages: the pre-transfer, the physical transfer of the patient to the operating theatre and post-transfer.

The IHT modelling lifecycle went through different iterations, allowing us to evolve the model from relatively dense, unstructured notes to processes, and thus progress from an informal to a formal representation. The first round involved modelling information extracted from a set of hand-written

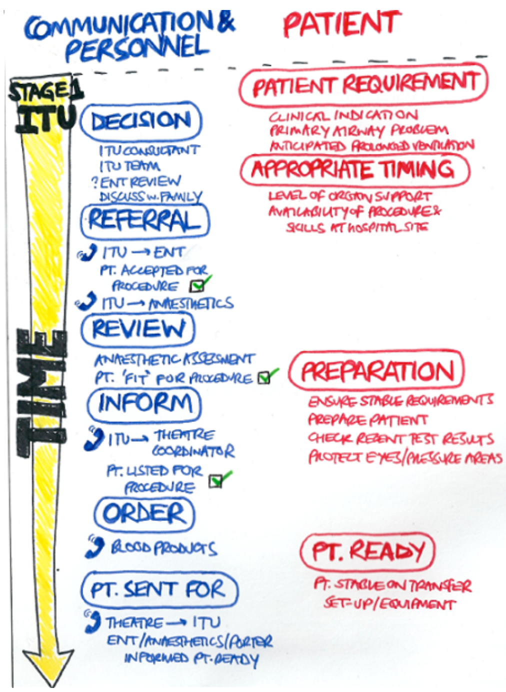


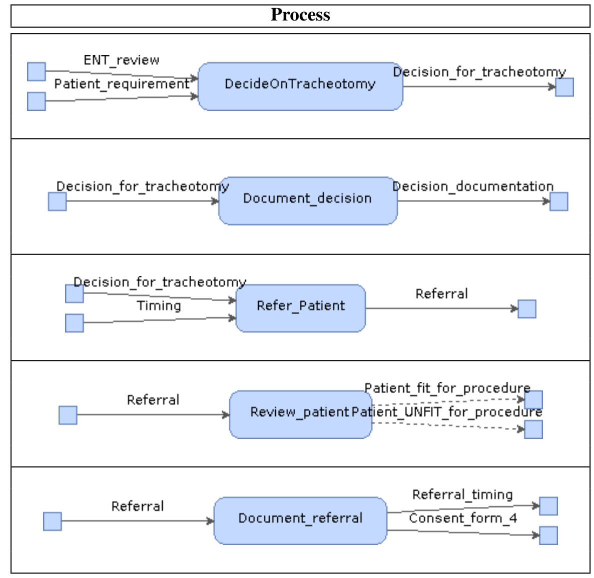
Fig. 1. Hand-sketched flowcharts for tracheostomy transfers

notes provided by our medical collaborators. After encouraging the medics to reflect over the flow of IHT tasks, they then provided us with a set of flowcharts that distinguished between different IHT stages and demonstrated a separation of concerns with respect to communication and personnel, patient, equipment and documentation (see Figure 1 for an extract). Given these flowcharts, we established a process-based model, which was thereafter continuously revised based on feedback from our medical collaborators. With the use of our visual tool, we then modelled the tracheostomy transfer processes. As the visual modelling occurred, the logical specifications of the processes were constructed automatically in the underlying logical engine.

The final model of tracheostomy transfers consists of a varying number of processes for each stage. Thirteen processes are captured for the pre-transfer stage, during which there is a decision for tracheostomy, the patient is referred, reviewed and prepared to be sent for the operation, transfer equipment is prepared and checked, and relevant information is communicated between different members of staff. One process is identified for the second stage, during which the patient is physically transferred to the operating theatre. Eleven processes are captured for the post-transfer stage, during which the patient is positioned, anaesthesia is performed, the personnel prepares for and performs the surgery, and the patient is prepared to be transferred back to the ICU.

An extract of the process-based model developed for the pre-transfer stage is presented in Table I, showing the first five processes of this stage, along with their inputs and outputs. The process *DecideOnTracheostomy* involves making a decision for a patient to have a tracheostomy surgery. This decision is based on the ENT review, which identifies clinical indications such as tracheostenosis, and any patient-specific requirements, such as oxygen requirements. The decision for

TABLE I. EXTRACT OF TRACHEOSTOMY TRANSFER PROCESSES



tracheostomy is a prerequisite for referring the patient for the surgery through the process *Refer_Patient*. Another input of this process is *Timing*, which refers to whether the timing is appropriate for the patient to have a tracheostomy, for instance whether the patient is unstable. The process *Review_Patient* takes place only if there is a referral for that patient, and it involves carrying out an anaesthetic review of the patient for tracheostomy. This review may deem the patient to be fit or unfit for surgery, and hence *Review_Patient* has an optional output, namely either *Patient_fit_for_procedure* or *Patient_UNFIT_for_procedure*. If the patient is found to be fit for the procedure, the pre-transfer stage progresses so as to make any preparations needed to send the patient for the transfer. In the case where the patient is assessed as unfit, an exception is thrown and the transfer does not take place. Our study of tracheostomy transfers at St Mary's Hospital revealed that documentation processes are highly important for the transfers, as several documents are required for the surgery and are often physically transferred along with the patient to the operating theatre. Two documentation processes are included in Table I, namely *Document_decision* and *Document_referral*. The former involves documenting the decision for the patient to have a tracheostomy operation, and it is a prerequisite for sending the patient for the transfer. The latter involves reporting details about the appropriateness of the timing for a tracheostomy surgery, as well as completing *Consent_form_4*, which is a form for adults who are physically unable to consent to medical investigation or treatment.

B. Formally Composed Workflows for Tracheostomy Transfers

The defined tracheostomy transfer processes were composed with the use of our graphical tool, thus providing us with a visual representation of the transfer flow. The composed workflow was rigorously verified on-the-fly, enabled by the formal foundations of our approach that allow for the corresponding logical proofs of correctness to be automatically constructed in the background. The outcome of the composition process is a set of three visual, but formally correct, workflows for the different transfer stages, which can then

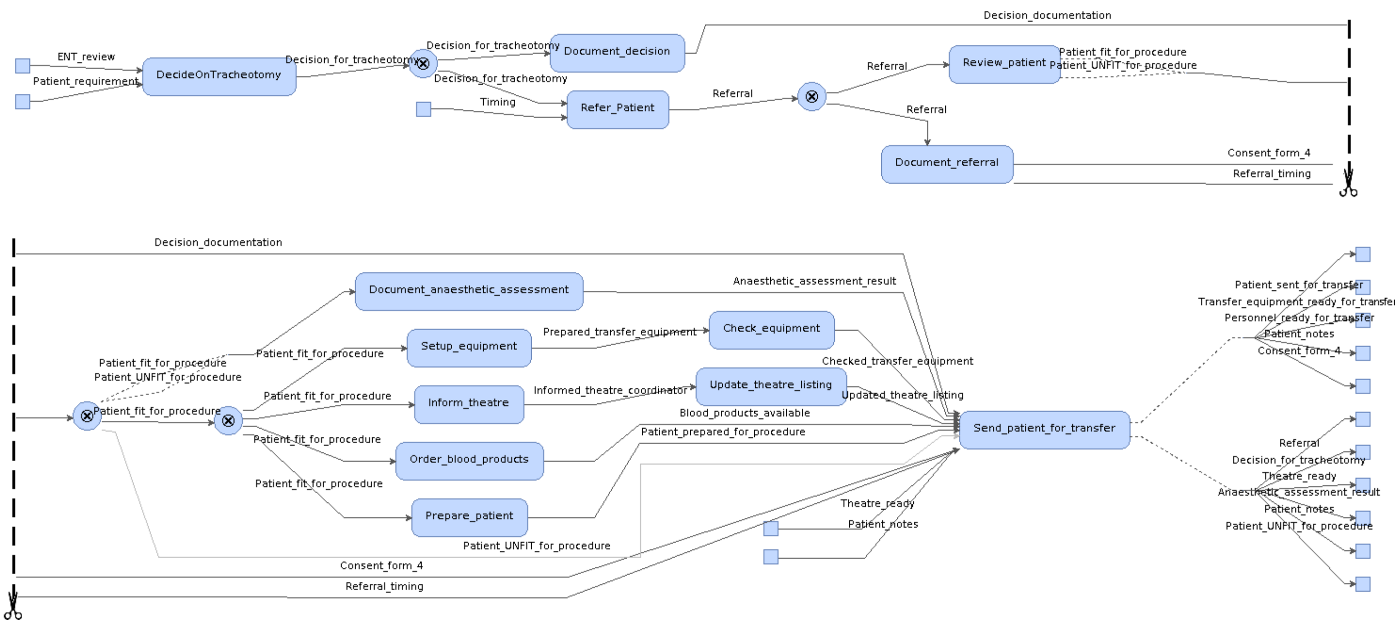


Fig. 2. Composed worfklow for tracheostomy pre-transfer stage

be further combined to obtain a final workflow for the entire tracheostomy transfer lifecycle.

The workflow developed for the pre-transfer stage is presented in Figure 2. The top part of this figure visualises the composition of the processes presented in Table I, while the lower part refers to the preparation of the patient and resources (e.g. transfer equipment and blood products) to be sent for the transfer. Due to space limitations, we describe in detail only the top part of the workflow, highlighting what one can learn from its study. In this, the dependencies between processes are graphically captured, for instance *Review_Patient* depends on the execution of *Refer_Patient*, since a *Referral* is required as an input for *Review_Patient*. Similarly, it becomes clear that certain processes that may be perceived to be related are in fact independent, such as *Document_referral* and *Review_Patient*, which can be carried out without influencing one another. Furthermore, the progression of the pre-transfer stage is clarified by the workflow, which makes evident the sequence of process execution. For example *Refer_Patient* takes place before *Review_Patient* and after *DecideOnTracheostomy*, while *Document_decision* takes place after *DecideOnTracheostomy* and at any point before *Send_patient_for_transfer*. This way, one can deduce based on the workflow that certain processes can run in parallel with others. *Document_decision* and *Document_referral* are two such cases, which can be carried out concurrently with almost the entire lower workflow branch. Enabling such observations is crucial, and it can have a direct impact on an efficiency improvement undertaking at St Mary's Hospital. The information lifecycle is also reflected in the workflow, making it possible to track, for instance, that the decision for tracheostomy is transformed into a referral and next into a review of the patient as fit or unfit. More importantly, this information flow is formally verified, and hence a medic that wishes to investigate further an anaesthetic review can confidently direct his/her search to referral- and tracheostomy decision-related information.

The most important point about the lower workflow part is the fact that the review output *Patient_UNFIT_for_procedure* is handled as an exception by the workflow. This is made clear from the two groups of outputs of *Send_patient_for_transfer*: The upper group refers to the successful completion of the pre-transfer stage, while the lower group corresponds to its unsuccessful termination due to the exception. The rigorous process composition demonstrated a subtle point about the case where a patient is assessed as unfit for tracheostomy at St Mary's Hospital: The patient transfer cannot be aborted until the *Anaesthetic_assessment_result* is documented.

The high-level, final workflow capturing tracheostomy transfers at St Mary's Hospital is presented in Figure 3, depicting the three transfer stages. This workflow, which was obtained by rigorously combining the three lower-level workflows for the different stages, makes it possible to track the flow of resources throughout the entire transfer lifecycle. For instance, it can be seen that *Patient_notes* are an input of the first stage, they are transferred with the patient during the second stage, and they are again required as an input for the third stage. The two groups of final outputs differentiate between the successful and unsuccessful termination of a tracheostomy transfer, in a similar way to the workflow presented in Figure 2. We should emphasise that deriving these two output groups at different levels of abstraction for transfers at St Mary's Hospital would not have been as straightforward without the automated reasoning capabilities of our tool.

C. Benefits

The workflows obtained through our framework provide a clear model of intra-hospital transfer procedures that is tailored to individual hospitals. Furthermore, the adoption of a rigorous approach to modelling and verifying intra-hospital transfer workflows brings important benefits that can contribute to improving the safety of the transfers. The five main benefits are now discussed.

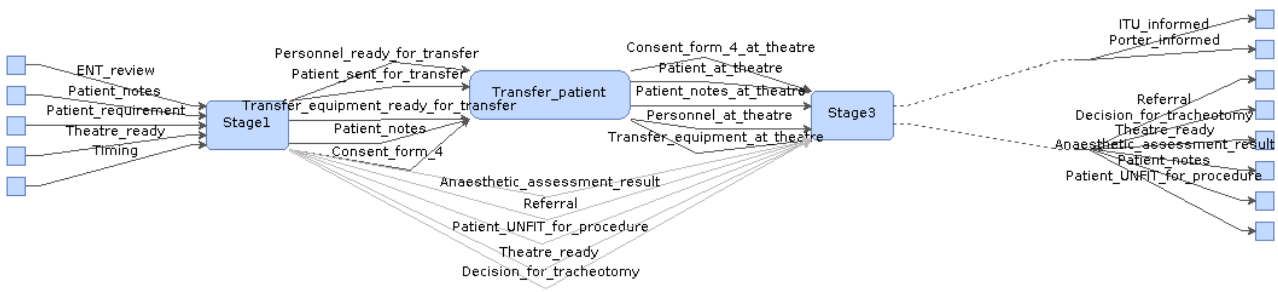


Fig. 3. Higher-level composition of tracheostomy transfer worfklow

First, a formal model of previously ad-hoc transfer procedures is provided, capturing the main transfer tasks, their dependencies and sequence of execution. This clear, unambiguous representation of existing informal practices is a prerequisite for potential healthcare improvement initiatives. Second, thanks to the rigorous verification capabilities of our approach, mathematical guarantees are provided for the configuration of the transfer workflows, which can thus be trusted to be correct. In the case of tracheostomy transfers at St Mary's Hospital, the medics were thereby able to confirm that the followed procedures were essentially correct, including the postponement of some documentation tasks until the patient is ready to be sent for the transfer. Third, the information flow during intra-hospital transfers can be traced, as already discussed in Section III-B. This means that typical miscommunication problems, such as redundant or missing information, can be tracked in the workflow model for resolution. Fourth, transfer-related resources, such as equipment and documentation, are systematically accounted for, and thus it becomes explicit that a process cannot be carried out unless all its preconditions are satisfied. This feature can help reduce errors and delays caused by missing resources. Finally, exceptions are explicitly handled, and their effect on the transfer progress is formally and visually represented. A relevant example at St Mary's Hospital was discussed in Section III-B, namely the exception thrown when a patient is assessed as unfit for surgery.

The case study of tracheostomy transfers at St Mary's Hospital serves as proof-of-concept, demonstrating the feasibility and usefulness of our approach in a real and demanding hospital setting. Tracheostomy transfers at St Mary's Hospital are complex, and they include a wide range of tasks carried out by a varying number of healthcare practitioners with different expertise. Capturing these was a laborious process that required close collaboration with staff at St Mary's Hospital. It is worth stressing, however, that moving from an initially underspecified and "fuzzy" conceptualisation of the transfers into an explicit and reliable model of the transfer tasks, resources, dependencies and progression would have been much more challenging without the logical foundations of our approach.

At the same time, the workflows developed for tracheostomy transfers were perceived as coherent and unambiguous by our medical collaborators, who were able to understand them without having workflow-related expertise or any experience of formal modelling and verification. More importantly, the visual, process-based model of the transfers provided them with insight into their local procedures and helped them reflect systematically on their current practice, thus bringing about stimulating discussions about potential improvements such as the automatic generation of checklists from the workflows.

IV. Related Work

Workflow-based approaches are widely used in the healthcare domain to provide automated IT support for clinical practitioners [2]. Representative examples include Tallis [18], one of the leading tools for the specification and enactment of clinical applications, and EON [19], a component-based architecture for the acquisition and execution of clinical guidelines. Languages for representing worfklow-oriented clinical guidelines include PROforma [20], Asbru [21] and GLIF [22]. The main advantage of our framework compared to the above is the formal verification of the composed workflows and their automatic deployment as executable models that enforce hospital policies. These are considerable strengths when studying informal procedures involved in intra-hospital transfers, as the constructed workflows are supported by mathematical proofs, hence allowing a high level of trust. It is also worth mentioning that instead of concentrating on medical decision-making like most existing workflow-based solutions, our focus is instead on organisational aspects, which often have a significant impact on the quality of patient care. As our case study demonstrates, documentation and communication aspects of intra-hospital transfers are perceived as important by clinicians, and thus their modelling, improvement and computer-based support are valuable undertakings.

V. Future Work

As already discussed in this paper, the model of intra-hospital transfers helps healthcare practitioners understand their everyday practices. With the aim of further improving this understanding, we will next extend our approach with simulation capabilities that capture time- and cost-based aspects of patient transfers. We are now working towards mapping the current formalism to SCOlog [23], a knowledge-based framework for simulating and analysing complex systems that measures the time and cost of workflow execution. We believe that SCOlog's automated explanation support and disruption propagation tracking mechanisms can effectively contribute to improvement efforts.

Deploying the composed workflow as an executable solution is also part of our future plans. We will build on our existing work for automated workflow deployment to generate electronic checklists and create a software workflow system that supports hospital staff throughout the transfers and enforces related clinical guidelines. This will allow for an end-to-end healthcare solution, that models typical scenarios, analyses different cases and enables their improvement through automated, computer-based means.

We also wish to explore the usefulness of our approach for addressing other important healthcare matters, such as the care of patients with long-term conditions. We are currently involved in the HIV Implementation and Improvement Programme in Scotland, and, with the help of leading HIV specialists, are studying local HIV integrated care pathways, which are considered as a key priority area [24].

VI. Conclusion

In this work, we presented a formal approach to the modelling and verification of intra-hospital transfer practices. A graphical tool for modelling and composing healthcare workflows is built on top of the logical foundations of our work, thus providing fully visual yet rigorous mechanisms for workflow composition. This way a formal model of previously informal, ad-hoc procedures during intra-hospital transfers is developed, which provides mathematical guarantees that the procedures are verified with respect to both the consistency of the information flow through the individual processes and the systematic matching of their preconditions and effects.

The feasibility and applicability of our approach was demonstrated through the case study of intra-hospital transfers for tracheostomy at St Mary's Hospital, London. A rigorous and visual workflow model, developed through a close collaboration with staff on the ground, allowed a range of stakeholders to gain an insight into various informal procedures and their inter-dependencies. This clear and visual account of case-specific practices can complement generic guidelines and policies, thus providing a more representative picture of healthcare systems.

We believe that the modelling enabled through our framework can serve as a good basis for standardising intra-hospital transfers and explicate potential safety issues. Inefficiencies in the sequence of transfer processes can be discovered, communication requirements can be fully specified and tracked, and the course of actions in the case of an exception can be explicitly prescribed.

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