

# Integrated modelling of medical emergency response process for improved coordination and decision support

George Milis<sup>1</sup> ✉, Panayiotis Kolios<sup>1</sup>, Gaby Van Melick<sup>2</sup>, Toni Staykova<sup>3</sup>, Ira Helsloot<sup>2</sup>, Georgios Ellinas<sup>1</sup>, Christos Panayiotou<sup>1</sup>, Marios Polycarpou<sup>1</sup>

<sup>1</sup>KIOS Research Center for Intelligent Systems and Networks, University of Cyprus, Aglantzia, Cyprus

<sup>2</sup>CrisisLab, Renswoude, The Netherlands

<sup>3</sup>Cambridge University Hospitals NHS Foundation Trust, Cambridge, UK

✉ E-mail: milis.georgios@ucy.ac.cy

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The medical emergency response comprises a domain with complex processes, encompassing multiple heterogeneous entities, from organisations involved in the response to human actors to key information sources. Due to the heterogeneity of the entities and the complexity of the domain, it is important to fully understand the individual processes in which the components are involved and their inter-operations, before attempting to design any technological tool for coordination and decision support. This work starts with the gluing together and visualisation of the interactions of involved entities into a conceptual model, along the identified five workspaces of emergency response. The modelling visualises the domain processes, in a way that reveals the necessary communication and coordination points, the required data sources and data flows, as well as the required decision support needs. Work continues with the identification and modelling of the event-driven discrete-time-based dynamics of the emergency response processes and their compositions, using Petri nets as the modelling technique. Subsequently, an integrated model of the process is presented, which facilitates the parallelisation of the tasks undertaken in an emergency incident.

**1. Introduction:** The medical emergency response domain encompasses multiple heterogeneous entities. In the framework of the CONCORDE EU project [1], the primary focus is to facilitate emergency incident response as it happens in real life, addressing the central needs of operational units, being those that bear the brunt and are in direct contact with the patients. To achieve such a feat, the solution is not based upon formal disaster management structures, but rather based upon insights into the needs of the emergency incident response, the way it happens in real life and as gathered from incident evaluations and other research [2–5]. Due to the fact that medical aid provision is time-sensitive, it is clear that it involves much rapid decision-making and immediate action taking by those in the field. Operational units have to decide upon and undertake the right actions and provide the right care to a patient within a limited amount of time, while the stakes (human life) are high.

The decisions are made upon the information available, therefore having accurate information is crucial. Due to the time pressure, it is likely that medical professionals decide based on locally available information. In most cases, involving small-scale emergencies, the operational decisions are rather straightforward. That is, Emergency Medical Services (EMS) staff need to make fast assessments of their patients' injuries, status and needs, after which they just as rapidly decide upon a course of action. Such decisions and actions are quite standard and they are taken within the context of daily operating procedures.

However, medical emergency response is not always as straightforward. Daily operating procedures might not suffice, especially when it comes to large-scale emergencies that pose distributed problems, i.e. many decisions must be made in complex situations where available information is spread over many actors and tasks usually have to be performed by actors in different geographical locations and not in possession of that information. Due to the dynamic and complex circumstances, there is often little and/or ambiguous information, and thus much uncertainty. Adequate decision making with regard to the emergency as a whole thus becomes more of a challenge.

During large scale incidents, emergency service organisations (police, fire services and medical care units) relapse into their regular daily operational procedures and therefore act in accordance with their institutionalised tasks. In other words, in emergencies the professional responders will take the actions they always would take; i.e. they will offer medical care to the first victim they come across, they will deal with the first fire they see and so on. This is addressed in the scientific literature as naturalistic decision making [6].

At present, many countries have formally adopted a three-tier command structure (often referred to as the bronze, silver and gold command level [7]), for the deployment and coordination of emergency services. As shown above, however, setting priorities and coordinating measures via a centralised decision making tree [8], can hardly be achieved in practice. The answer to these coordination difficulties would be the deployment of distributed decision making (DDM) [9, 10]. In DDM, complex problems are cut into smaller ones, whose size matches the individual's information-processing abilities. Individual units are called to make their own decisions, independently, but considering the overall objective. Enabling DDM will facilitate frontline units to complete the necessary operational tasks since decentralised actors have been proved to be doing the right thing if they are provided with the right information. The CONCORDE project, thus, aims at developing a software system that will facilitate the decision making of several actors at different levels and will offer the means of effectively communicating the decisions to the appropriate actors. The value will be created from collating (and even creating) all fragments of (localised) information in a meaningful way, thus building situational awareness and enabling informed decision-making.

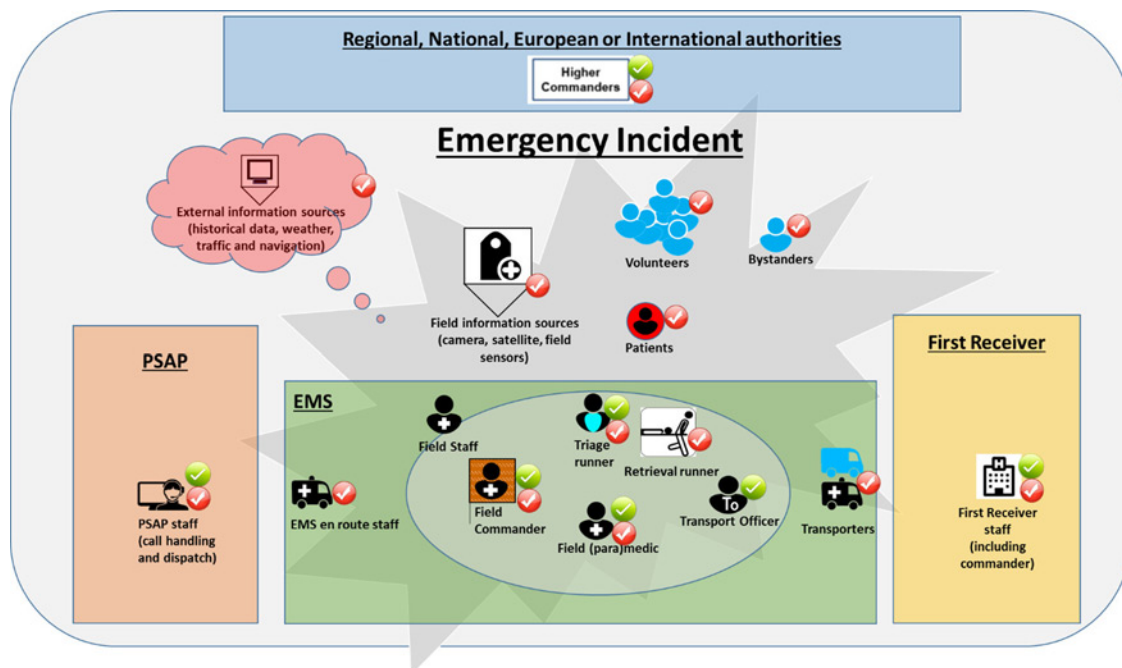
This Letter describes an effort towards achieving an integrated model of the medical emergency response process, combining event-driven time-based dynamics with conceptual integration links and communication flows. The result enables the complete understanding of the dynamics of individual sub-processes, their interactions with the rest of the components and the exact points and effect of decision making nodes.

The rest of the Letter is outlined as follows: Section 2 identifies the main organisations and actors participating as components in the medical emergency response process. Section 3 follows with the presentation of a visual conceptual model of the emergency response process, which captures the interaction and communication among the organisations and actors throughout the process. Section 4 then introduces the need for breaking the overall process into smaller parts and studying the discrete-event dynamics involved with these sub-processes. This leads to Section 5 that presents the integration of the individual discrete event models, in line with the conceptual model. Finally, Section 6 concludes the Letter and discusses future directions.

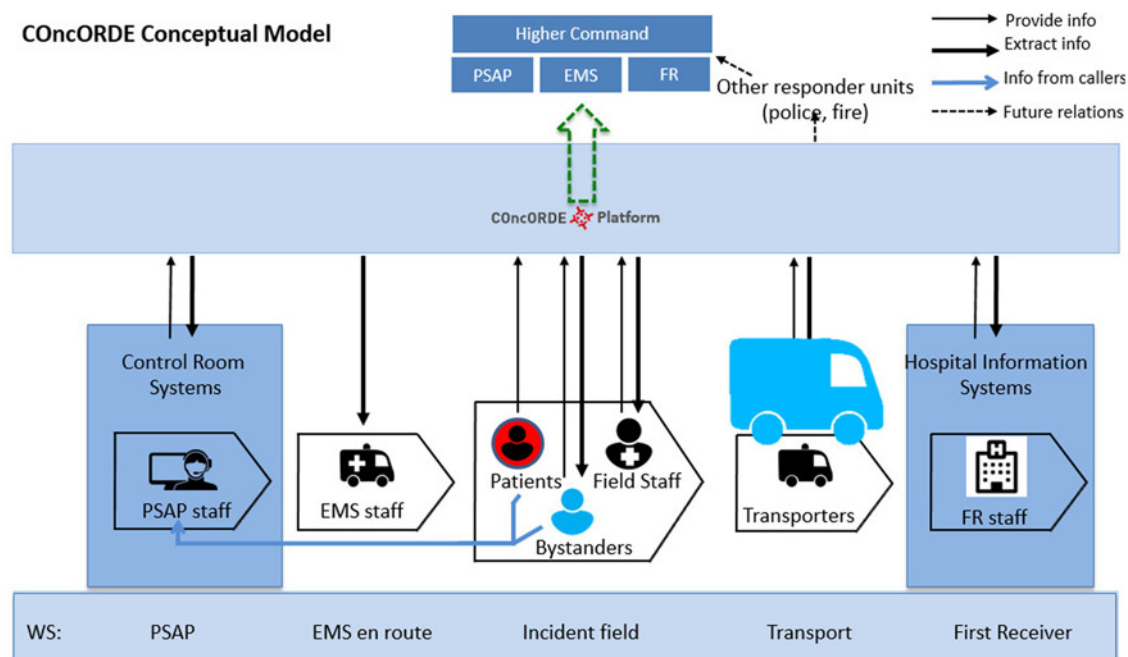
**2. Modelling of domain entities:** The medical emergency response ecosystem comprises both physical and virtual entities which interact with each other and are interdependent when dealing with an emergency incident, forming an integrated whole. These entities comprise the directly involved parties such as public-safety answering point (PSAP) control centres, EMS (including field healthcare professionals and supportive staff), transport services, first receiver services, volunteering services, bystanders and so on, as well as the indirectly involved parties such as regional, national and international higher-level decision makers. In practice, other operational response services like fire brigade, search and rescue teams, police and so on, also communicate and coordinate their activities with the EMS via their commanders, however, these interactions are out of the scope of our work and are not discussed here. Fig. 1 presents the identified components within the medical emergency response process, including their characterisation in terms of their decision making role and use of tools. It can be seen that the following entities are considered in this work as being directly involved in the medical emergency response process:

- **Higher commanders:** they are responsible for the higher-level decision making and communications at regional, national, European, international levels. They are called to make higher-level decisions during large-scale incidents that, e.g. require upscale for resource allocation, as well as to provide the link to the higher level and wider boundaries.

- **PSAP/112:** it includes both call handling and dispatch operators. The former are the operators that respond to calls of the public alerting about emergency incidents. The latter are responsible for the initial deployment of response resources and undertake also the initial decision making about which EMS units to dispatch to the incident field.
- **EMS en route staff:** they represent the EMS units that have been dispatched and are travelling towards the incident field.
- **EMS field staff:** it involves all staff operating on the incident field, including the: (i) incident commander that, among others is responsible for the allocation of field sectors to triage runners and retrieval runners, as well as for allocation of other field resources to patients; (ii) field (para)medics that undertake the actual emergency medical treatment of the patients at the second triage stage, as well as the allocation of medical resources to patients; (iii) the triage runners that perform the first-level triage/tagging of the patients, defining priorities for treatment; (iv) the retrieval runners that transfer the patients from their initial locations to the field's medical treatment area; and (v) the transport officer that undertakes the allocation of patients to transport vehicles and first receivers.
- **Transport staff:** they are the EMS or other vehicles and staff that undertake the transportation and in-transit treatment of patients from the incident field to first receivers (hospitals or shelters).
- **First receiver:** it includes the commander of the first receiver that takes over the patients and undertakes the allocation of medical staff and other resources to them, as well as the rest of the medical staff that provide the treatment.
- **Bystander/volunteers:** they are members of the general public of organised volunteers under non-governmental organisations (NGOs). Depending on their declared capacity, they can assume roles such as caller, medical aid assistance providers, runners, retrievers, transport staff and so on.
- **Patient:** they are the victims themselves that can play the role of the caller alerting about the incident and/or help other more seriously injured victims on the field.
- **Data sources:** it includes surveillance (camera) data, satellite data, traffic and navigation data, social media data, weather data, epidemiology data, historical injury data, Chemical, Biological, Radiological, Nuclear, & Explosive (CBRNE) data, incident field sensor data about smoke, heat, radiation, seismic activity, chemicals and so on. All listed data sources are (potentially) used for decision making.



**Fig. 1** Medical emergency response entities (legend: green tick describes component involves decision making and red tick describes component involves use of existing tools)



**Fig. 2** Visual representation of the medical emergency response conceptual model

The involvement and the dynamics of the above entities in medical emergency response processes are described in the following sections.

**3. Visual conceptual modelling:** The modelling exercise of the medical emergency response process, starts with a visual representation of the interoperation and communication flows, showing on an abstract level the relation of all organisational/human actors as entities of the overall process (Fig. 2). This visual representation adds extra value by incorporating the five workspaces of the medical emergency response [1], thereby showing the spatial (and time-wise) distribution of the actors. The higher command is placed at the top, since the aim of the CONcORDE project is not to build a centralised system ruled by higher command, but rather to allow the system to follow the natural actions of the distributed users in their roles and enable their interlinking. The model focuses upon facilitating the (operational) actors in the horizontal line of emergency response, where operational actions take place. It can be seen that the process starts with the alerting of the PSAP staff at the Control Room about the incident, continues with the travelling of EMS resources to the field, then managing the field operations, leading to transferring the patients to First Receivers (hospitals or shelters). It is expected that actors along this process, will be facilitated with one and/or two-way communication and information exchange through a core platform. In order to build an added-value platform, it is important to first model the dynamics of individual parts of the process, so as to properly identify the interaction points and the mutual effect of undertaken actions. The latter is the main contribution of this work.

Zooming further into the model and especially when it comes to the third workspace, the incident field, there is value in a more detailed representation, as there are many different roles and tasks for different actor groups (Fig. 3). The model introduces also the Medical Treatment Area (location where victims are moved for first-aid) and the Primary Victim Location (being the location where victims initially are found) and shows in more detail the spatial distributed nature of emergency response. It can be seen that all field actors require two-way communication and

information exchange so as to facilitate local decision making for optimal and timely performance.

It is understood that different types of emergency incidents may impose different challenges on the emergency response services. For instance, a natural event like an earthquake may have different effect than an accidental flood or a malicious terrorist attack. The differences mainly lie in the expected casualties and the type and number of resources to deploy for the appropriate response. This is related to the decision making process and is facilitated through the offered communication links and the subsequent information sharing. However, the response process itself remains unchanged. The differences do not affect the modelling in this and the following section, but are captured by the instantiations of the models.

Another important aspect of the integrated process is the time required for the completion of the process. In current practice, the information about the status of the patient is not communicated in a very consistent and reliable way and it also does not become available at the time of its creation. Therefore, the initial check of patients' records and the allocation of resources delays for longer. In order to improve the situation, the CONcORDE system aims at making information about patients' status available to medical staff immediately upon its creation, keeping it updated by triage runners and retrieval runners during the operation of their tasks. This enables the preparations for the allocation of resources to patients to start earlier, thus facilitating the transition to happen earlier in time. Such time-savings result to a significant contribution to the medical emergency response domain. To aid visualisation, Fig. 4 shows the parallelisation of work in the emergency response workspaces. For instance, the role allocation by Field Commander can start before the arrival of any EMS units, or transportation to first receivers by bystanders that obtain information about hospitals' bed capacity, might start before formal field operations are up and running and so on.

The following section deals with breaking the process into smaller parts and modelling the dynamics of these parts, so as to correctly identify the integration points and needs.

**4. Discrete-time event-based modelling:** The medical emergency response is considered as a large process covering the full domain with complex dynamics and is comprised of smaller processes

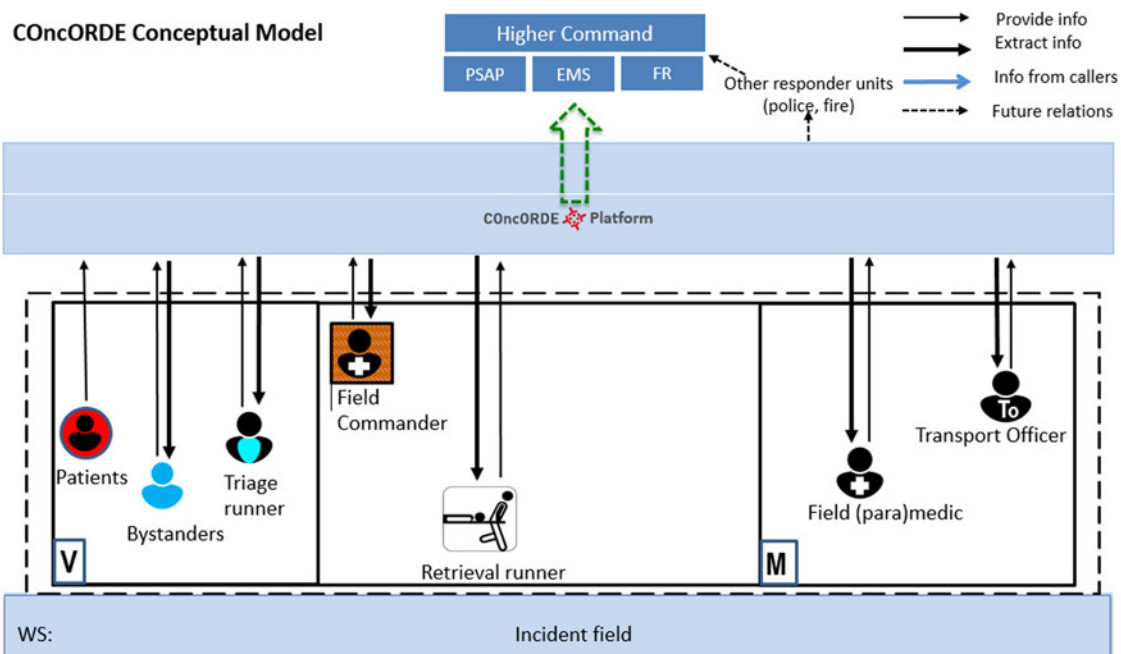


Fig. 3 Zooming into the conceptual model of the incident field workspace

(offering services by or through the involved entities). Adopting the system-of-systems concept [11], each process is modelled separately and then a larger process will be modelled as a network with the individual processes as nodes. It is also noted that the modelling must be such that the cooperation of the individual processes is able to achieve the objectives of the larger system without compromising the objectives of the individual ones. Table 1 lists the adopted breaking of the overall medical emergency response process into smaller parts.

It has been discussed that many of the listed sub-processes are currently running sequentially due to lack of direct information exchanges as soon as information is gathered. The time-based dynamics modelling, captures the intermediate transitions (e.g. dispatch decision using pre-existing knowledge, information and

invitation to EMS units involved) and the process-states (e.g. exact resources of each type to be dispatched, available resources in all EMS organisations in the area). Although some parts of the medical emergency response process can be considered as having continuous-time dynamics, the decisions are only taken and implemented at discrete times and therefore at macroscopic level the response is more naturally modelled as discrete-time. Moreover, since the changes happen upon the occurrence of events, the dynamics are further considered as event-driven. Therefore, a discrete-event approach was the most reasonable to model the relevant sub-processes, as separate (dynamic) subsystems:  $\Sigma^{(i)} = 1, \dots, n$ .

The Petri nets (PNs) have been adopted as an appropriate modelling technique, [12]. A PN is a directed bipartite graph with vertices being either 'places' or 'transitions'. 'Places' are furthermore

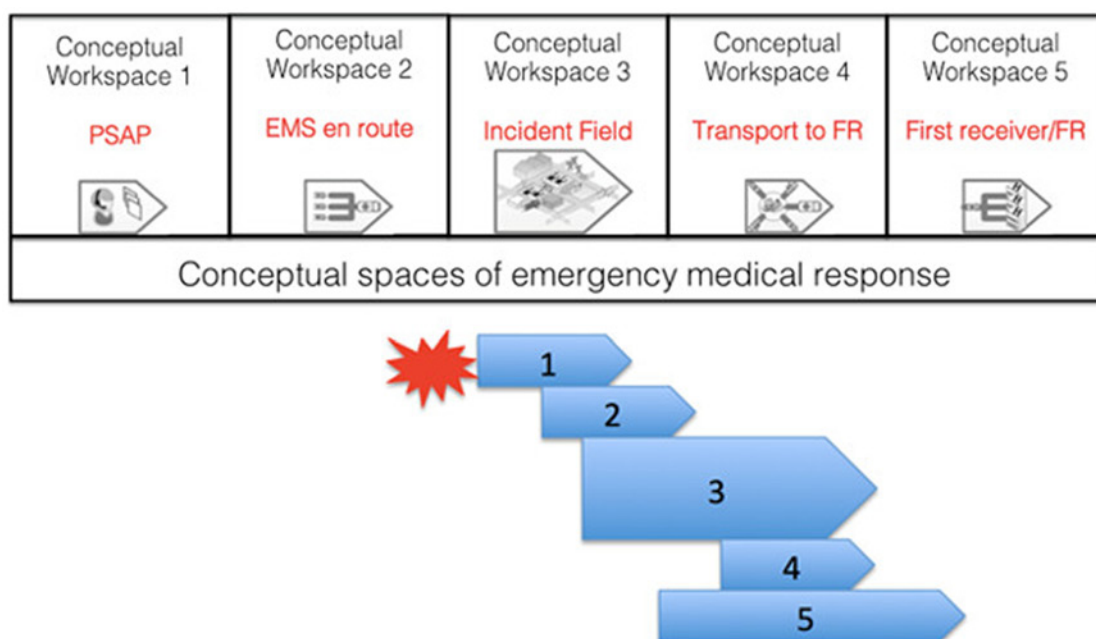


Fig. 4 Representing the fast-tracking response activities for efficiency gains, from serial to parallel



**Table 1** List of identified and modelled sub-processes

ID	Sub-process name
sub-process 1	higher-level decision making
sub-process 2	responding to incident calls/alerts
sub-process 3	decision for dispatching EMS units
sub-process 4	decision to upscale
sub-process 5	travelling to the incident (EMS en route)
sub-process 6	establishing command, cordon and control
sub-process 7	incident command and management
sub-process 8	patient triage/tagging (level 1)
sub-process 9	patient retrieval
sub-process 10	patient medical treatment and triage (level 2)
sub-process 11	patient transportation allocation
sub-process 12	patient transportation to first receiver
sub-process 13	patient handover to first receiver
sub-process 14	taking over patient
sub-process 15	allocation of resources to arriving patients
sub-process 16	bystander/volunteer actions
sub-process 17	patient actions
sub-process 18	obtaining field data from available data sources

marked by ‘tokens’. Transitions are considered enabled if their input places contain at least one token. When enabled transitions are fired, one token is removed from each input place (pre-condition) and one token is added in each output place. The reader is referred to [13, 14] for a more detailed introduction to PNs. It is straight-forward to map processes into PNs, since processes are basically ordered sets of operations. Operations can be modelled by transitions, while the state of a process (service) can be modelled by places. The arrows between places and transitions are used to model causal relations. It is also assumed that a PN, which represents the behaviour of a process, contains at least one input-place (i.e. a place with no incoming arcs) and at least one output-place (i.e. a place with no outgoing arcs).

In its more general form, the PN model of a process is given by the five-tuple of the following equation

$$\Sigma^{(I)} : (\mathcal{P}^{(I)}, \mathcal{T}^{(I)}, \mathcal{A}^{(I)}, c^{(I)}, x_0^{(I)}) \quad (1)$$

where

$\mathcal{P}^{(I)}, \{p_i^I | i = 1, 2, \dots, n^I, p_i^I \in \mathcal{N}\}$ : the set of ‘places’ of the PN, which represent the state of the process. The places have ‘markings’ (with tokens), i.e. values in the set of physical numbers.

$\mathcal{T}^{(I)}, \{t_i^I | i = 1, 2, \dots, m^I\}$ : the set of possible transitions that can happen due to occurrence of specific events.

$\mathcal{A}^{(I)}$ : the set of connections (arcs) between network places and transitions. It essentially represents the state-transitions. The set is usually split into the set of input places of transitions (pre-conditions), e.g.  $\mathcal{I}^{(I)}(t_i^I) = \{p_j^I | (p_j^I, t_i^I) \in \mathcal{A}\}$ , and the set of output places of transitions (results), e.g.  $\mathcal{O}^{(I)}(t_i^I) = \{p_j^I | (t_i^I, p_j^I) \in \mathcal{A}\}$ .

$c^{(I)}$ : the vector of the weights of the arcs  $\mathcal{A}^{(I)}$ . It essentially denotes the cost of the transitions, i.e. the corresponding conditions to be met for the transition to be enabled.

$x_0^{(I)}$ : the vector of initial markings of places.

To further clarify the meaning of the above in the model, a specific example is provided below, assuming the model of a process that represents the allocation of resources to patients arriving to a first receiver (a hospital to which patients are transferred from the emergency incident location).

• *States of the process*: (i) the number of available resources (emergency beds, emergency nursing staff, emergency doctors,

quantities of available supplies used in emergency rooms etc.) and (ii) resources allocated to patients.

• *Transitions in the process*: (i) decision for resource allocation, (ii) moving of resource to patient and (iii) lost resource. The transitions form controlled or uncontrolled ways to modify the identified states.

• *Other parameters that affect the process*: (i) knowledge about available resources, (ii) knowledge about status of patients and (iii) knowledge about status of incident. These are variables that do not directly characterise the state of the process (e.g. the number and type of resources allocated to patients), but they do affect the operation and the state transitions.

The mechanisms through which all of the above operate and affect the change of the system-states, is captured by the set of arcs and the way they connect the places through the transitions, as well as by the weighting of these arcs. For instance, the event of bringing emergency beds in the hospital, causes a direct transition that increases the respective state. Where necessary, the model may incorporate uncertainty in the resources (through uncertainty in the firing of transitions) by considering stochastic instead of deterministic transitions which in turn cause uncertainty in the marking of places (value of states). It is noted also that the output place of a process, may correspond to an input place of another process, thus enabling meaningful compositions.

The PN models of the identified processes have been created with the use of the Netlab tool [15]. The tool uses a natural numbers’ counting of the ‘places’ and ‘transitions’, however, these are important only for reference purposes while explaining each model. The number of a place is the one on top, while the number at the bottom represents the current state-value, against the maximum capacity. For example, 1/8 means the current value of this state is 1 while the maximum capacity is 8. Two PN models are given here as indicative examples of the complete exercise, while the complete list of the models can be found in [1].

Fig. 5 presents the created model for the ‘sub-process 2: responding to incident calls/alerts’. It can be seen that the input to the process is a call that arrives to report an incident. Depending on the incoming of such a call and also on the availability of call handling operators (parameter), the answering of the call will fire the transition to a hidden state that models the calls currently being served. As long as there are active calls being served, two transitions can be fired; one leads to the creation of a new incident log (referred to as Incident e-Form) in case the call refers to a new incident and the other is the update of an existing incident log in case the call refers to previously reported incident. The latter are modelled as two outputs of the process. In addition, while calls are being served, they may be dropped, which will cause the transition to a state where a call handling operator returns back to available. There is also the possibility for the call to be forwarded to another PSAP (if the content suggests so), which will cause another output of the process (this output may serve as input to another instantiation of the same process).

Then Fig. 5 presents the created model for the ‘sub-process 8: patient triage/tagging (level 1)’ that is executed on the field. The deployment of triage runners, in combination with the knowledge about dangers on the field, the location of patients and any navigation hints in the field, enables the arrival of runners to the patients (transition ‘log arrival to patients’ and state ‘triage runners to patients’). Then the triage runners can perform the level 1 triage (transition ‘Perform Triage Level 1’) given that they have access to or know by heart the triage algorithm and they also have at their disposal a tool to record the triage results. The outputs of the process are the triaged patients (O1) and also the sharing of the information (O2) with the Incident Field Commander and others, as required.

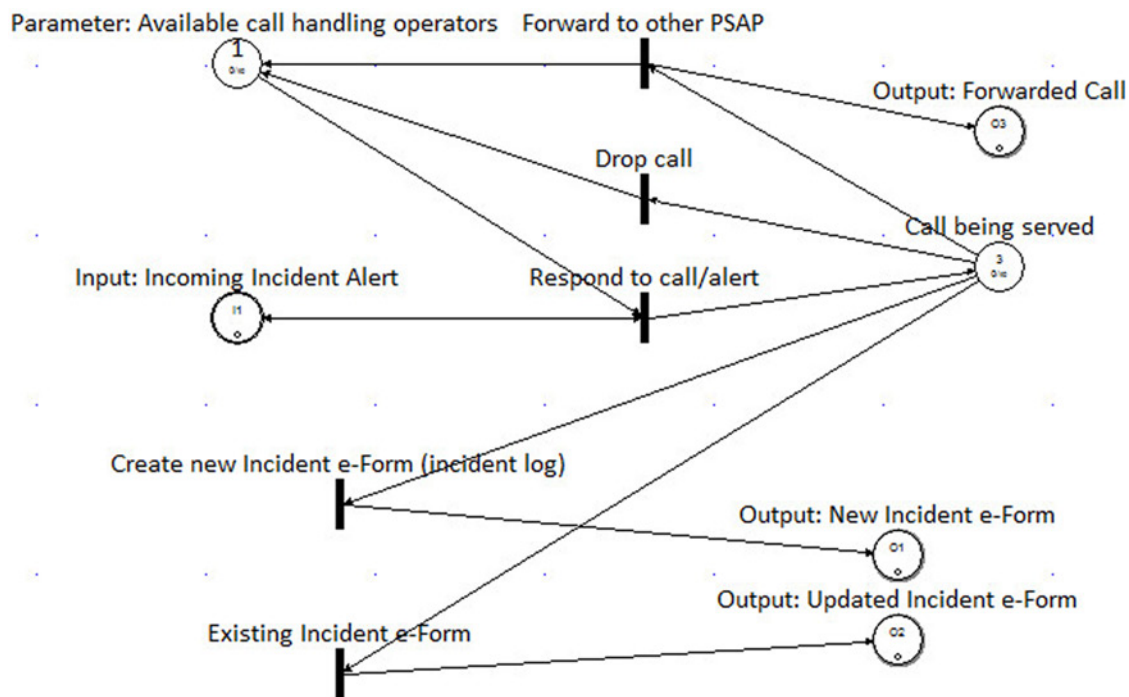


Fig. 5 PN model of 'sub-process 2: responding to incident calls/alerts'

A full model of an incident response would combine the models of the sub-processes into a single PN model. By assigning times or ranges of times to the transitions (possibly including suitable distributions), response times to more composite processes can be calculated via a relevant simulation software. This can be repeated for the current practice in emergency response as opposed to the one enabled by the modelling and parallelism of the actions, to give a measure of the possible improvement in terms of efficiency in response and in terms of advancing the state-of-the-art. The integrated model that enables this type of simulations and evaluations, is presented in the following section.

**5. Integrated discrete-time event-driven model:** It has been mentioned that the result of the modelling exercise is the composition of all individual processes into a single PN model. The compositions are implemented by the intervention of transitions and/or places between the outputs of one sub-process and the inputs of another sub-process. For instance, the composition as shown in Fig. 7 implements the transition from a call action to the response within the PSAP. The part of the model

that implements the composition is highlighted with thick red lines. The complete set of compositions' models can be found in [1].

In addition, an example of an enactment of the composite model is given here, through a usage scenario from the CONCORDE project.

*Caller:* Ian travels on a high-speed train and suddenly hears an explosion. The train derails and he is thrown out of the window on a nearby field. He can feel a pain in his leg and some part of his body is bleeding. He calls 112 and the operator starts asking questions. It turns out the operator knows his location from his phone call. He takes details and asks him to wait for the ambulance since he cannot walk. Ian sees that there are many others lying around injured. *Operator:* The operator receives a 112 call on Ian and when he looks at his screen, he can see where the caller is calling from. He logs the call and the documentation starts.

In the above scenario, a patient is lying down and calling to request help and report the incident, of which he furthermore possesses a

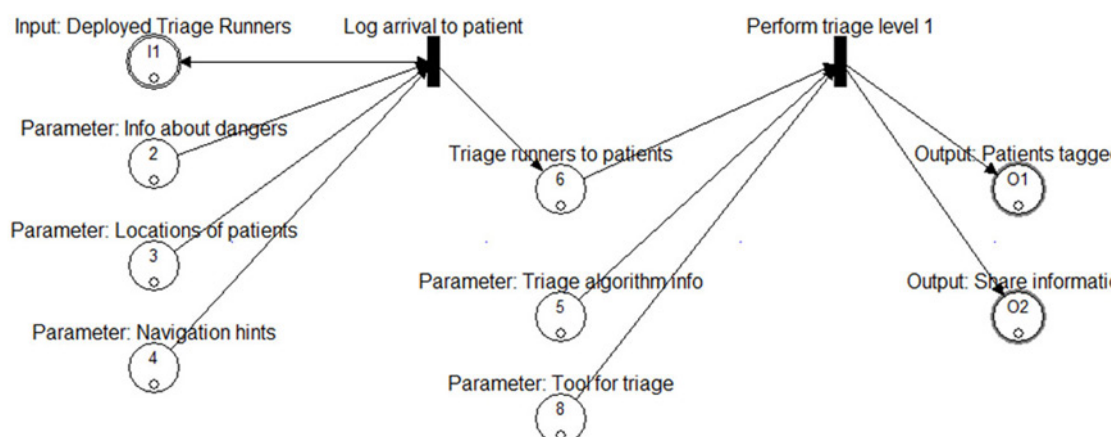


Fig. 6 PN model of 'sub-process 8: patient triage/tagging (Level 1)'

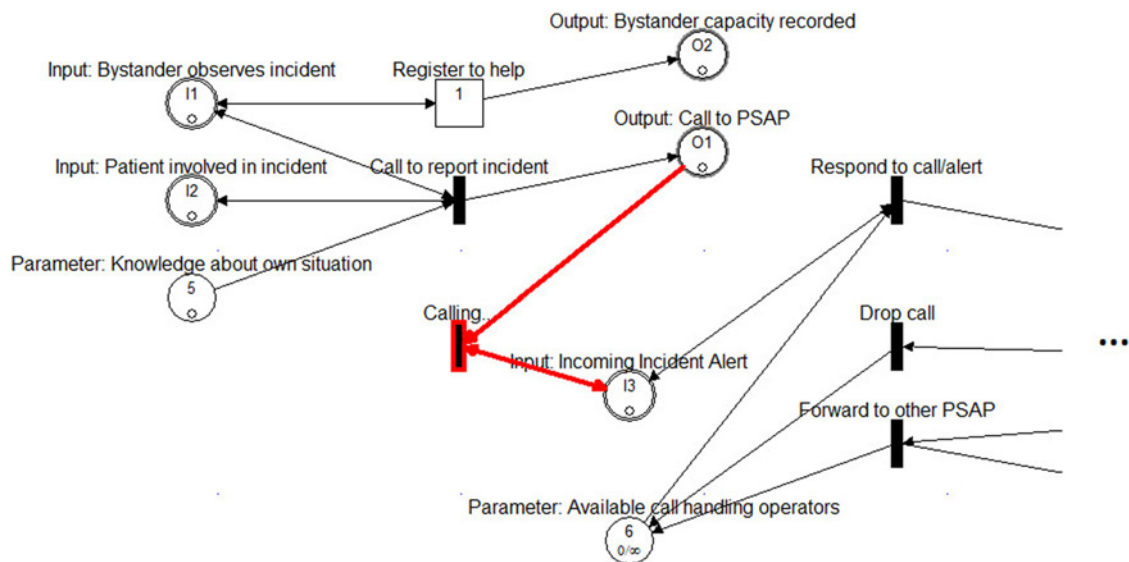


Fig. 7 Composition of sub-processes 'bystander/volunteer actions' and 'responding to incident calls/alerts'

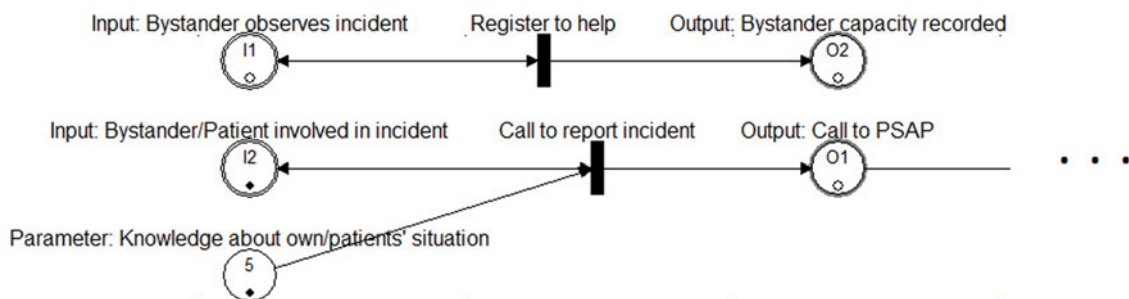


Fig. 8 Composite model: scenario enactment, step 1

partial awareness beyond his own condition. This activates the transition 'Call to report incident', as shown in Fig. 8. The call happens, which means the transition fires, and this leads to the state 'Call to PSAP' being reached.

The reaching of the aforementioned state, activates the transition 'Calling...' of Fig. 9. The alert call arrives to PSAP and since there are available call handling operators, the transition 'Respond to call/alert' is enabled. The answering of the call marks the state 'Call being served' and at the same time it enables the transitions 'Create new Incident e-Form' or 'Update Incident e-Form', as well as the transitions to drop the call or forward it to another PSAP (Fig. 10).

The call corresponds to a report of a new incident, therefore the relevant transition is fired and a new Incident e-Form opens for editing, thus enabling the transition 'Creating Incident e-Form'.

*The operator has a computer terminal with predetermined questions to ask in order to define what happened, determine Ian's needs and the priority. He/she asks about name and age of the patient and records them, as well as about what happened.*

The predetermined questions, help the operator to recognise the type of the incident and other details and also help define the exact response

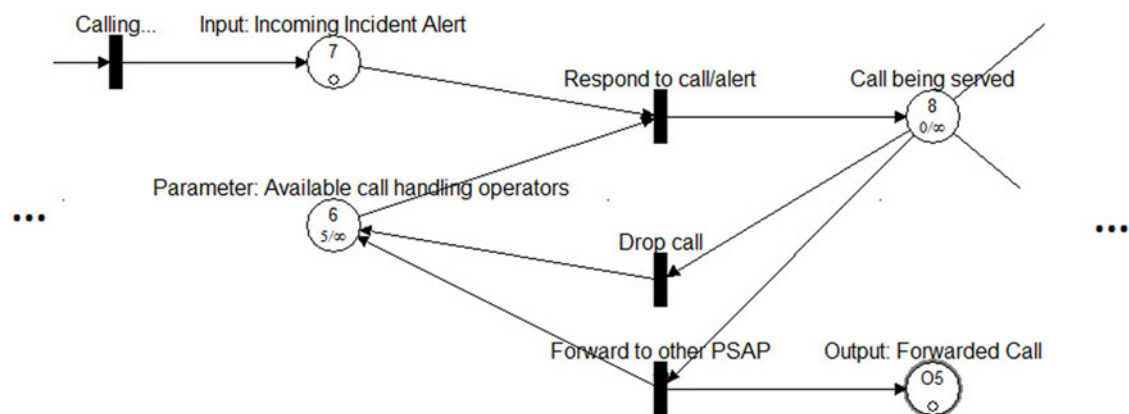


Fig. 9 Composite model: scenario enactment, step 2

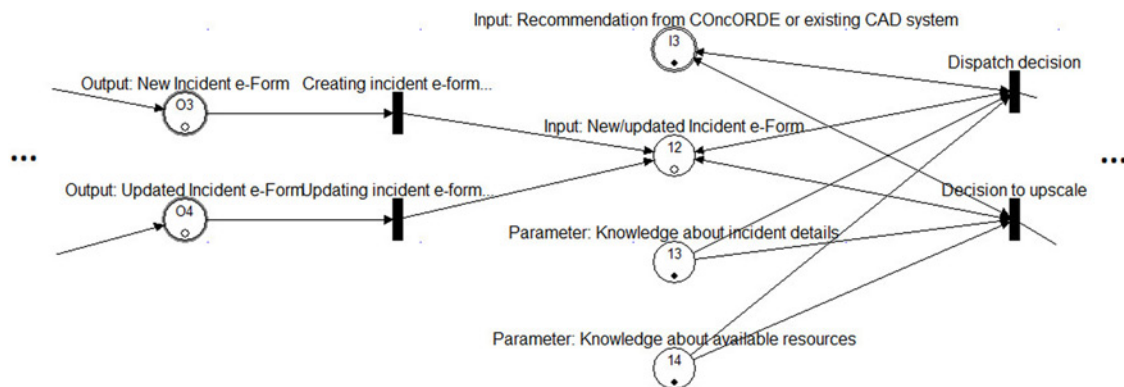


Fig. 10 Composite model: scenario enactment, step 3

needs and the priority, which are then documented along with all details gathered. The operator also has a computer-aided dispatch (CAD) system that supports him in making the dispatch EMS decision (number and types of resources to be sent to the field). It is also assumed that the dispatch operator has access to the incident log, as well as to the incident map with the availability of resources, through the COncORDE system (see marked parameters in the model). Following the collection of all relevant information, the PSAP operator completes the initial logging, which is modelled by the firing of the transition and the marking of the state 'New/Updated Incident e-Form' as shown in Fig. 10. This state enables the transitions related to making the decision of dispatch or requesting upscale.

The modelling continues until the whole emergency response process is completed. Similar to the part of the scenario enacted above, even more complex scenarios can be executed, while all necessary resources are tracked by the PN models. The modelling exercise shows that a network of nodes can be established to model the interdependencies, the state evolution and the causality of events in emergency response processes.

**6. Conclusions:** The work attempted an analysis of the medical emergency response domain, in terms of dynamics' and conceptual interactions modelling, towards the design of a technological tool for coordination and decision support. The approach has been spherical in the sense that it first captured visualisation of emergency response interactions, it then went deeper into analysing the interactions and interdependencies of individual actors/processes and modelling the shift of resources across them. The aim is to use the created models to build knowledge and help take informed decisions. It is emphasised that tracking the dynamic state of the medical emergency response, offers many advantages to the implementation of correct and meaningful decision making using appropriate algorithms (e.g. multi-objective resource allocation [16], prediction of demand for resources [17] etc.). In addition, future work will also focus on integrating the decision support algorithms with semantic profile data of incidents, thus enabling decision making based on better situational awareness.

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