Active Tokens for Modelling Mental Health Care with Coloured Stochastic Petri Nets

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Abstract

Petri nets are a well-known paradigm for simulating dynamic systems. Coloured Petri nets are characterised by tokens with attributes whose values are changed by events in the model. They cannot play an active role in the system behaviour. Using them to model human beings, with continuously changing attributes and simple decision-making abilities, would require a large number of auxiliary elements in the net, resulting in a significant loss of clarity in the model. In this paper we would like to introduce the concept of active tokens in coloured stochastic Petri nets that enables the modelling of changing attributes independently of system events and without adding further elements to the net. The proposed concept extends the tokens by methods for event-independent attribute dynamics. We demonstrate the principle of active tokens by an example from mental health care.

1. Motivation

Understanding the behaviour of dynamic systems is often difficult due to complex causal relationships of the system elements involved. Computer simulation has established itself well for this kind of problem, as it allows these relationships to be modelled in an abstract manner. With the aid of such a simplified representation of the real system, the user is able to gain detailed insights into system states and events and their impact. In this way, it is possible to analyse and optimise the systems' behaviour according to pre-defined objectives. The results provide a basis for detailed capability planning to support decision makers and researchers.

These kinds of simulation studies are widely spread in industry and, in particular, find use in the examination of logistical processes. In the field of health care applications, which are often more complex than just a sequence of logistic events, computer simulation is less accepted. The main reason is the involved "human factor" that leads to a number of influences in the model which are not needed in industrial applications. If considered at all, a human being in logistics is usually seen as a passive resource in the process, whose attributes are predetermined or can only be modified by system events. Depending on the goal of the simulation study, this narrow perspective may be insufficient for the analysis. Instead, the simulation of a health care system may require the modelling of human beings as active elements that can both move around within the system, (a mobile element), and also have attributes that can change independently of events.

In the field of mental health care, where the mobile element is a patient taking part in psychiatric services, the simulation is additionally complicated by the fact that many of the attributes are psychological ones, such as satisfaction or motivation. These are of qualitative nature and, as a consequence, hard to measure and compute. Furthermore, there are complex interdependencies between these kinds of attributes. To be able to insert these parameters into the simulation model it would be necessary to know and compute the development of all attributes prior to the simulation run, which is a non-trivial problem. Nevertheless, computer-assisted planning is of great interest for service providers of mental health care services, for both resource planning and optimising the medical care. For this reason, we are currently developing a simulation model of the German mental health care system.

In this paper we introduce a new way of modelling systems with the involvement of active mobile elements with attributes that are independent of system events. As we would like to focus on the application to the modelling of human beings in mental health care, we present a simplified example from psychiatry that illustrates the issue of dynamic and interdependent mental attributes and thus the idea of the proposed modelling concept.

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2. Approaches for Modelling Dynamic Systems

2.1. System Dynamics

The concept of System Dynamics, developed by Jay W. Forrester in the 60s, delivers formalisms for the understanding and modelling of dynamic systems [1]. It has been applied to many application fields within a short period of time and since the 70s there have been efforts to model processes and causal relationships of health care systems using System Dynamics [2].

The principle of systems thinking views the system from a broad perspective and tries to find overall structures, patterns and cycles. The involved entities are seen as a homogenised unit although they are individuals with different attributes [3]. This is insufficient for our project, as we are interested in the flow of individual entities through the system, to be able to evaluate strategies and decisions that are directly related to the patient as an active mobile element. The influence of events and the resulting state changes cannot be implemented within the System Dynamics concept. Nevertheless, the formalisms developed by Forrester are a helpful tool for developing a first understanding of the processes and interdependencies of the system.

2.2. Agent-Based Modelling

Software agents provide the opportunity of modelling active mobile elements with dynamic attributes such as patients in medical applications. Thus the concept could be used for modelling the desired mechanisms computing the attributes.

But an "intelligent agent" describes much more than just the kind of mobile element we intend to model [4]. For analysing and understanding the mental health care system, the patient object neither has to be able to develop action plans for putting its own goals into practise nor has to have mechanisms for machine learning and automated reasoning. Furthermore, detailed knowledge about the environment and aspects of interaction and cooperation with other objects in the system are not necessary.

An agent-based model of our system would not utilise the principal strengths of the concepts of intelligent agents – merely the dynamic change of its parameters. This is only a small benefit and does not justify the time and effort for the development of an agent "patient" and a computationally intensive multi-agent simulation. For these reasons we decided against an agent-based model.

2.3. Petri Nets

Petri nets are a common and easily accessible paradigm for modelling state- and event-based systems. The complete system is represented as a graph consisting of places (states) and transitions (state changes due to occurring events) that are connected by directed arcs. The places of the net can contain any number of mobile elements of the system, referred to as tokens. These tokens are moved from place to place by the "firing" of the transition representing an event in the system.

A transition does not have to fire immediately when a token is added to an input place. It may instead have a deterministic or stochastic time delay. Petri nets with randomness in the transitions are called Stochastic Petri Nets [5].

Coloured stochastic Petri nets extend the concept by adding attributes to the tokens [6]. The firing of a transition not only changes the distribution of tokens but can also modify the attributes of the tokens.

The most important advantage of Petri nets is the graphical representation that gives a clear and intuitive overview of the system. During the simulation run, the user is able to track the movement of tokens through the system. The whole definition of the system is revealed without hiding information or functionality. Furthermore, the net is easily extended by adding places and transitions – even for a user without expertise in modelling techniques. This is of interest to us, since the model we are developing is to be used by medical, rather than modelling, experts.

The graphical nature of Petri nets is also a disadvantage. When modelling carelessly, the net can easily become hard to read. Although it would be possible to model each event by a transition, whether the event is part of the interesting logistic process or not, the resulting Petri net would contain a huge amount of auxiliary transitions that do not represent the main system processes. This violated one of the primary basic concepts of Petri nets and it is recommended to refrain from using this kind of modelling style.

System Dynamics is a very abstract approach and agent-based modelling a very comprehensive one covering much more functionality than we are actually interested in. Coloured stochastic Petri nets capture the right amount of detail for our purposes. Although the computation of changing token attributes will be important for the quality of the simulation study, the expected user of our model will be mainly interested in getting an overview of the systems processes when looking at the simulation. For these reasons we chose to use coloured stochastic Petri nets and to extend them to include autodynamic token attributes.

3. A New Approach with Active Tokens

Stochastic Petri nets are called *coloured* if the tokens have attributes making them distinguishable from each other, as "non-coloured" tokens of simple Petri nets are drawn by convention as black dots. The attributes of each token are represented by a simple or composited data type that is defined by the modeller. The value of a token is analogously referred to as token *colour* and the data types as *colour sets*. Furthermore, each place has an assigned colour set determining the type of token the place may contain. The current state of the system is called the *marking* and is determined by the distribution of tokens on the different places of the Petri net. When a transition fires, it changes the token position and thus the marking of the net. The firing can set the colour of the token by causing the recalculation of the value via defined transition operations. Nevertheless, this is – viewed from the perspective of the token – a passive process.

As described above, we are interested in modelling the transition-independent change of a token colour. This becomes necessary if the attributes of a mobile element are changing without a global system event happening. To implement this without additional transitions, we need to extend the definition of a token. In addition to the mere existence of one or more attributes, combined in the token colour, we need supplemental information about possible mathematical relationships between the individual attributes or the development of these attributes over time.

In the case of continuously changing attributes we add the corresponding differential equations and mechanisms for its solution. In the case of correlating attributes we have to extend the token definition by the declaration of regression equations. Furthermore, an internal timer is necessary to initiate the recalculation of the token colour at discrete time intervals while waiting for one of the connected transitions to fire. In this manner, the token receives a state and mechanisms for the autonomous examination of that state. For this reason, the extended mobile element is referred to as an *active token* – in contrast to a passively driven element without dynamic attributes.

As each mobile element is part of the system, the change of that element causes a change in the system state. Accordingly, a new token colour implies a new state of the Petri net and thus a new marking of the net that is not a result of a transition firing and the related token movement. The new marking can lead to the enabling and also disabling of connected transitions.

The advantage of the implementation of active tokens is that the clarity of the graphical representation of the Petri net is retained. The processes going on in the system can still be recognized just by looking at the tokens moving through the net. This has a positive effect on the system analysis and, in addition, the expense for possible extensions of the net. After expanding the token by a state and calculation methods, it is more than a passive element. By characterising the token as active, the difference between an ordinary logistic element and a human element becomes clearer.

Putting the dynamics of the attributes into the tokens has the further advantage of an explicit separation between global changes of the system and local changes of the mobile elements. There is a clear encapsulation of both processes and thus they can be adapted independently. But this encapsulation can also be seen as a disadvantage, as the original concept of Petri nets encourages the idea of a completely transparent functionality where no mechanism is concealed. However, in coloured Petri nets, this transparency is already violated to certain extent.

Another basic principle of Petri nets is the clear limitation of the modelling process to defining states and events of systems. A change might have unpredictable or unintentional effects on the behaviour of the net, e.g. effects on occurrence rules or the marking of the net. Therefore, expanding Petri nets by transition-independent changes of token colours requires a detailed examination of possible consequences.

Introducing active tokens will have an effect on the computational effort of simulating the net in comparison to the traditional coloured stochastic Petri net, as we add supplementary computational methods of various complexities. Nevertheless, we expect a positive effect on the expense for the development and implementation of the overall simulation study.

4. Motivating Example

In order to illustrate the issue of dynamic attributes of mobile elements we give a simplified model of the health care services in a psychiatric hospital which disregards other types of services such as ambulant treatment or community psychiatry.

The mental attribute we would like to use is the so-called *compliance*. Compliance describes the motivation of the patient for taking an active part in the therapy and complying with the instructions of the medical personnel. This attribute is an important parameter in mental health care. The reason for this central position lies in the fact that the compliance has a direct and strong influence on the therapeutic outcome and thus the probability of getting ill again. In psychiatry this plays a more decisive role than in other fields of medical care such as surgery or internal medicine. In an extreme case the patient will discontinue the therapy and leave the psychiatric facility.

The level of compliance at the beginning of the therapy varies from patient to patient and changes continuously during the course of the treatment. It is possible for example, that the compliance is low initially, then increases due to therapeutic successes and then continuously decreases the longer the treatment takes, while different forms of therapy can cause different courses [7]. The change can be completely independent of events occurring during the hospital stay, although some can have an effect, for example the visit of relatives or special activities organised by the medical personnel during the hospital stay. Additionally, compliance depends on further mental attributes that may themselves have a continuous dynamic. As a result, all these parameters have an impact on the compliance and thus on the probability of therapy discontinuation by the patient as exemplified in Figure 1.

For implementing this dynamic in the simulation model, we would have to precompute the development of those attributes, which is a non-trivial problem. In the model we use in this paper we consider the mood of the patient as well as the subjectively observed treatment complexity as influencing factors.

Furthermore, as this precomputed parameter is artificially designed and not measurable for the "real patient", it is not only difficult to understand for the medical personnel but also difficult to use in simulation experiments. A change during a simulation run, when testing a therapy strategy that should increase compliance e.g., is difficult to carry over to reality for designing possible policies.

The logistic part of the process of hospital treatment consists of only a few states and events that can be modelled by a simple coloured stochastic Petri net. Figure 2 gives an overview of the system.

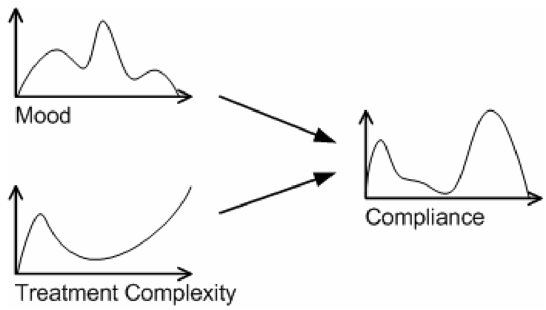

Figure 1. Mental attributes influencing the compliance

The Petri net consists of the places "InTherapy" and "Released" that mark the two states the patient can be in. Both places have the colour set "Patient", meaning that they can only contain tokens of the type "Patient". The transition "Admission" adds these tokens to the place "InTherapy" and models the event of entering the hospital, e.g. via referral from a general or psychiatric practitioner. By doing so, the token colours "Diagnosis", "Compliance", "Mood" and "Complexity" are set to a randomly distributed initial value. The attribute "ProbabilityOfReadmission" can be set to zero. It will become relevant later. Now the supplementary methods added to the active token "Patient" can be used to compute the patients initial "WillToDiscontinue. In this example we assume that the chosen qualitative attributes can be scaled between 0 and 1.

First, the move from the state "InTherapy" to "Released" can only happen by finishing the therapy modelled by the transition "Finish". The firing of this tran-

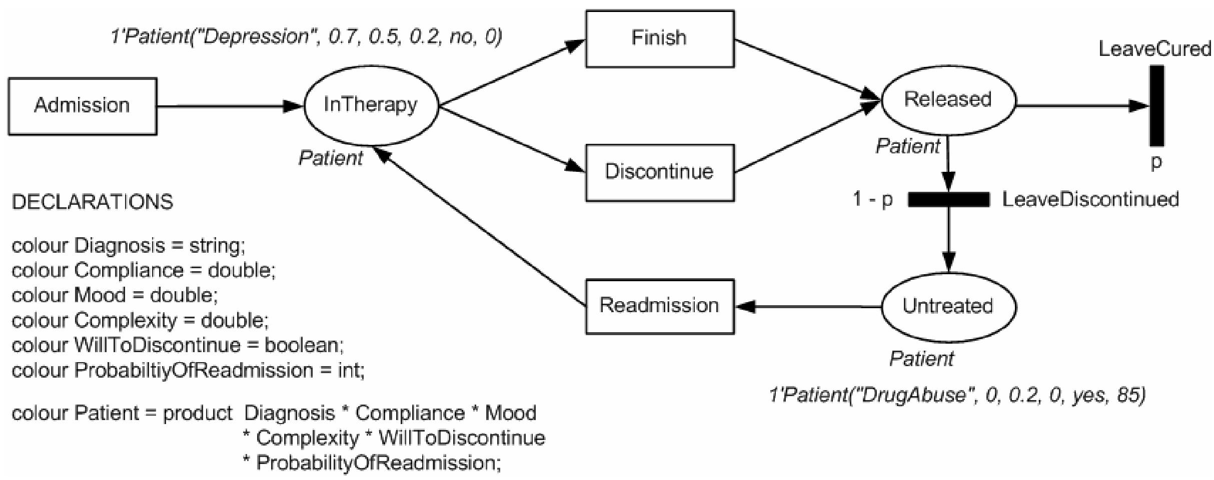

Figure 2. Petri net of health care service in psychiatric hospital

sition is determined by the token colour "Diagnosis" as different disorders require different forms of therapy of different durations. If the length of the hospital stay prescribed is 20 days for example, the token will have to remain 20 days in place "InTherapy" until the transition "Finish" occurs. For the above reasons, it is possible that the compliance falls below a certain threshold during this time – even without anything happening in the system – and the patient decides to discontinue the therapy. For implementing this decision as a state change we inserted the transition "Discontinue". The problem is to specify if and when the transition fires. As stated above, we are not able to precompute all influences on the patients' will to discontinue and thus are not able to specify the parameters for this transition in a satisfying way that matches the actual behaviour of a patient.

Since the active token has its own mechanisms for computing its colour independently of the firing of the transitions, it is able to update its Boolean attribute "WillToDiscontinue" at regular intervals and depending on the current values of the influencing attributes. The firing of the transition is now only determined by the value of the token colour "WillToDiscontinue". If it is true, the transition will fire and add the token to the place "Released". In this way it is not necessary to precompute a possible discontinuation.

For modelling the higher probability of getting ill again when stopping the therapy early, the token colour "ProbabilityOfReadmission" is set to a lower value if the transition "Finish" had fired and to a higher value in the case of "Discontinue". After being released there is the probability p that the patient will leave the system completely – modelled by the transition "LeaveCured" – and the probability 1-p that the patient will have to return to the hospital – modelled by "LeaveDiscontinued". Both transitions fire immediately. The amount of time passing until readmission is modelled by "Readmission". The patient remains in the state "Untreated" until readmission becomes necessary.

For modelling all possible events that may change the compliance and thus the patients' will to discontinue the treatment, a large number of auxiliary transitions need to be added to the net as different events have different impacts on the tokens colour. Each transition would hold another operation for updating the colour in the according way while the tokens are waiting for the transitions "Finish" to occur. Considering that the system we want to analyse consists of more than just a few states and transitions, it becomes clear that a modelling approach with auxiliary transitions is inappropriate and will make the understanding of the systems processes more complicated.

5. Conclusion and Outlook

The understanding of logistic processes of a complex system benefits from a strict separation between token dynamics and system dynamics. Active tokens encapsulate information and operations that may not be interesting for a user of the simulation such as planner or decision maker and thus simplify the system analysis. The other way round the more detailed modelling of patients' attributes and decision making abilities both contributes to the precision of the model and enables simulation experiments concerned with patient-related questions as the improvement of medical services.

To simplify matters, all qualitative human attributes of the presented example were scaled between 0 and 1. To capture the essential meaning of those parameters different quantification methods may be more suitable. Active tokens including computational methods will enable the implementation of the chosen techniques directly within the token definition. To be able to completely model the German mental health care system with the aid of active tokens, we need to formalise the concept and perform a detailed examination of the effects of transition-independent token attributes and their impact on the behaviour of the Petri net. The resulting paradigm may then contribute to the modelling of human beings in a logistic context in further fields of application.

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