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Using the Statecharts paradigm for simulation of patient flow in surgical care

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Abstract Computer simulation of patient flow has been used extensively to assess the impacts of changes in the management of surgical care. However, little research is available on the utility of existing modeling techniques. The purpose of this paper is to examine the capacity of Statecharts, a system of graphical specification, for constructing a discrete-event simulation model of the peri-operative process. The Statecharts specification paradigm was originally developed for representing reactive systems by extending the formalism of finite-state machines through notions of hierarchy, parallelism, and event broadcasting. Hierarchy permits subordination between states so that one state may contain other states. Parallelism permits more than one state to be active at any given time. Broadcasting of events allows one state to detect changes in another state. In the context of the peri-operative process, hierarchy provides the means to describe steps within activities and to cluster related activities, parallelism provides the means to specify concurrent activities, and event broadcasting provides the means to trigger a series of actions in one activity according to transitions that occur in another activity. Combined with hierarchy and parallelism, event broadcasting offers a convenient way to describe the interaction of concurrent activities. We applied the Statecharts formalism to describe the progress of individual patients through surgical care as a series of asynchronous updates in patient records generated in reaction to events produced by parallel finite-state machines representing concurrent clinical and managerial activities. We conclude that Statecharts capture successfully the behavioral aspects of surgical care delivery by specifying permissible chronology of events, conditions, and actions.

Keywords Health care · Hospitals · Surgical services · Patient flow · Simulation · Statecharts

1 Introduction

Computer simulation, an operations research technique for evaluating a system's performance, has been used extensively in modeling patient flow [1]. Simulation provides a method for evaluating proposed changes in healthcare delivery when intervention studies are not feasible because of ethical, safety, economic, or other reasons [2]. Other work has shown that patient-flow simulations improve understanding of relations among care steps by showing event chronology and changes in case volume and mix [3, 4]. Simulations have also been used to obtain performance estimates for alternative decision-making scenarios [5].

A variety of approaches was developed for constructing simulation models of healthcare processes [6]. The system dynamics represents aggregated patient flow as deterministic, continuous-time changes in the population size of a system's states [7]. Although system dynamics methods are used for understanding behaviors of an individual hospital

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department [8, 9] and the entire network of care in a region [10], their utility for assessing changes in healthcare organization, management, and policy is unknown [11]. Markov models, which represent aggregated patient flow by transition probabilities among states [12], are also widely used to evaluate healthcare policies [13].

In discrete-event simulations, the system's operations are represented by a set of states with transitions among states occurring when certain events take place [14]. Discrete-event simulations have been used to study outpatient clinics [15–17], emergency admissions [18, 19], peri-operative processes [20], and surgical scheduling [21–25]. In time–driven models, regular temporal advances synchronize these transitions, whereas in event-driven models, events may trigger transitions asynchronously [26]. Two approaches to constructing event-driven models are common in healthcare applications. The first, event scheduling, samples the moments when events occur from predefined distributions of times [27], whereas the second, process interaction, specifies the chronology of actions associated with such events [28]. It has been argued that discrete-event models are especially appropriate for simulation in healthcare because patients are subject to multiple concurrent processes [2, 6]. By simulating interactions between the processes that advance individuals through the healthcare system, these models represent reality more closely than models, in which moving between states is governed by predefined deterministic or probabilistic rules.

For a long time, however, no satisfactory frameworks existed for developing the specifications of discrete-event models. As a result, patient flow in surgical care is often described by a series of flowcharts showing a sequence of pre-specified activities, with a list of actions detailing each activity [29]. For example, scheduling elective surgery can be described through two activities: planning service-specific staffing and scheduling cases of individual surgeons within their assigned blocks of operating time [30]. In the real world, however, a simple list of actions does not adequately represent an activity, as there is often a complex set of temporal relations with other activities. For example, the unplanned emergency admission of a patient with a scheduled procedure will trigger changes in routine operating room (OR) activity and may lead to cancellations of other procedures and staffing adjustments.

The purpose of this paper is to examine the capacity of Statecharts, a system of graphical specification [31–33], for constructing a discrete-event simulation model of the peri-operative process. The Statecharts specification paradigm was originally developed for representing reactive systems by extending the formalism of finite-state machines through notions of hierarchy, parallelism, and event broadcasting [31]. Hierarchy permits subordination between states so that one state may contain other states. Parallelism permits more than one state to be active at any given time. Broadcasting of events allows one state to detect changes in another state. Although the Statecharts is increasingly being used for evaluation of systems' performance [34–36], no literature exists on its appropriateness for representing patient flow through the healthcare system.

In the next sections we discuss the reactive nature of surgical care using an example of the progress of a patient through the peri-operative process. We then introduce the Statecharts system of visual notation and explain how to use this system for simulating individual care paths. We conclude by briefly describing a framework for assessing healthcare policy using discrete-event simulation models constructed from Statecharts specification.

2 Patient progress through surgical care

Surgical care encompasses a continuum of activities through diagnostic, pre-operative, operative, and post-operative stages [37, 38]. During the diagnostic stage, the patient undergoes tests and evaluations to identify the condition causing illness, which may or may not require surgery. The pre-operative stage consists of all the clinical and managerial activities that take place from when a decision to operate is taken until the patient enters the OR. The operative stage lasts from patient entry the OR until recovery. The post-operative stage includes recovery care and treatment in an inpatient surgical unit and/or an intensive care unit (ICU) and ends with the discharge from hospital. In this paper, we use results of mapping cardiac services at a major teaching hospital in British Columbia, Canada, to illustrate patient progress through surgical care.

A patient who presents with symptoms of coronary artery disease is usually referred to a cardiologist, who evaluates the results of coronary angiography and recommends treatment. If coronary angioplasty is not indicated, that patient is referred to a cardiac surgeon, who assesses the need for and suitability of surgical revascularization. Patients who require immediate care are admitted to a hospital cardiac ward directly from the catheterization laboratory. Elective patients are scheduled for outpatient consultation with the cardiac surgeon.

If, following the consultation, surgery is deemed necessary, the surgeon's office registers the patient on an appropriate wait list and sends the request for OR time to hospitals where the surgeon has admitting privileges. The patient is then scheduled for pre-surgical assessment in a pre-admission clinic where an anesthesiologist assesses the patient's suitability for surgery and creates a care plan for the pre- and post-operative periods [39]. The procedure is postponed if the patient is deemed unfit for any reason. If necessary, the patient undergoes additional pre-operative investigations for assessment of surgical risks. Clinic staff provide education about the procedure and any preparation required at home.

The patient's access to surgery is managed through the scheduling of OR time [40]. Surgical scheduling staff identify the patients available for allocated OR time slots and reserve hospital resources to ensure appropriate care during and after the operation [41]. Patients are selected for scheduling both from hospital wards and from the surgical wait lists based on allocated OR time slots.

Patients may be admitted to the hospital through the emergency room, the same-day admission clinic, or the patient registration office. To allow optimal utilization of surgical suite resources, the hospital periodically releases blocks of OR time to various surgical services. Each service then places its patients on the OR schedule, with some operative slots set aside for emergency cases [42]. Any time that is not booked by a particular service is then made available to other services. Each surgical service selects patients from its wait lists and schedules operations on the basis of urgency, best use of allocated operating time, availability of hospital resources, and plan for discharge from the hospital. Once set, the schedule for a particular service may be changed to accommodate the needs of emergency patients, who have preferential access to hospital resources. On the other hand, scheduled surgery may be moved ahead if an OR time slot becomes available.

On the day of a scheduled procedure, the anesthesiologist and the attending surgeon assess the patient before transfer to the OR holding area. After the operation, the patient is taken to the post-anesthesia care unit for monitoring and treatment of possible side effects of anesthesia. The anesthesiologist performs a post-surgical assessment and the patient is transferred to ICU or to a hospital ward for further treatment [43].

While the patient is on the ward, a bedside nurse reassesses the patient's pain and other aspects of his or her condition. Once the patient reaches the point where oral analgesics are sufficient to control post-surgical pain, the primary surgical service takes over the task of following the patient. Finally, when the criteria for discharge are met, the patient is discharged from the hospital to home or to after-hospital care.

3 Reactive nature of surgical care delivery

Delivery of surgical services involves multiple concurrent activities and coordination of their outcomes [44]. Table 1 shows an example of managerial and clinical activities that constitute the process of cardiac surgical care at the British Columbia hospital. These activities have certain functions that are accomplished through a sequence of actions. For instance, scheduling the pre-surgical assessment requires notifying the nursing staff and the acute pain management service and ensuring the availability of the necessary equipment [45].

When peri-operative activities are autonomous as in simple temporal sequencing, completion of one activity constitutes the start of the next activity. When activities are interacting, certain activities produce events that initiate or disrupt the orderly progress of actions in other concurrent activities. For example, a decision for elective surgery initiates scheduling of the pre-surgical assessment by an anesthesiologist and scheduling of OR time, but a patient's cancellation of the surgery at a later stage will necessitate changes in several of these peri-operative activities. Conversely, if the patient is deemed unfit for surgery during the final pre-surgery assessment (because of, say, a pulmonary infection), this information is broadcast to other activities, and a new series of actions commences: OR and ICU bed become available for another patient, the patient is referred to another specialist, additional diagnostic tests are ordered, and the operation may be rescheduled.

These examples highlight features of a reactive system that we will be focusing on: hierarchy and interaction of concurrent activities [46]. Therefore, the peri-operative process can be abstracted as a reactive system involving various threads of transitions from one state to another. These threads are interrelated and can affect each other according to the occurrence of certain events under certain conditions such as clinical urgency and bed availability.

4 Statecharts

Like state machines, a statechart includes state-transition diagrams that represent a system's operations through discrete states and transitions from one state to another. These diagrams are directed graphs in which nodes denote states and edges denote transitions. The language of Statecharts extends the formalism of finite-state machines by including notions of state hierarchy, parallelism, and event broadcasting.

Hierarchy in the Statecharts system permits one state to contain other states; in the context of care delivery, this feature provides the means to describe steps within activities and to cluster related activities. Parallelism permits multiple states to be active concurrently; this feature provides the means to specify concurrent activities in the peri-operative process. Broadcasting of events allows one state to detect changes in another state and provides the means to trigger a series of actions in one activity depending on transitions that occur in another. The hierarchy of states determines the visibility of an event, i.e., where an event occurs relative to its parent machine, and which machines react to the event being broadcast.

Table 1 Clinical and managerial peri-operative activities

Place	Activity	Function
Outpatient clinic	Referral of elective patients for outpatient assessment	Patients presenting with symptoms are sent for consultation with surgeon
	Registration of elective patients on appointment list	Details of referred patients are registered
	Scheduling of elective patients for appointment	Time and duration of appointments are determined
	Outpatient appointments for elective patients	Indication for operation is assessed (by surgeon)
	Registration of elective patients on surgical wait list	Details of patients who require and decide to undergo the operation are registered
	Booking of elective patients for operation	Dates of operations are determined after consultations
Pre-admission clinic	Referral of elective patients for pre-surgical assessment	Patients accepted for surgery are sent for consultation with anesthesiologist
	Scheduling of elective patients for pre-surgical assessment	Time and duration of assessment are determined
	Pre-surgical assessment	Suitability for surgery is assessed (by anesthesiologist)
	Scheduling of elective patients for new assessment	Time for assessment is determined for patients requiring further tests or unfit for surgery
Hospital	Referral of patients requiring urgent specialist assessment	Patients requiring urgent assessment after angiography are referred (by cardiologist)
	Scheduling of urgent patients for assessment	Time and duration of assessment by on-call surgeon are determined
	Scheduling of elective patients for in-hospital assessment	Time of admission and assessment by on-call surgeon is determined
	In-hospital assessment of patients requiring urgent treatment	Suitability of patients for admission to hospital as inpatients is determined
	Registration of inpatients in surgical queue	Details are registered for patients who must undergo the operation and who are admitted directly to hospital
	In-hospital pre-surgical assessment of elective patients	Suitability for surgery is assessed (by anesthesiologist and surgeon)
	Scheduling of OR time	Inpatients and elective patients waiting for operation are identified, and hospital resources are reserved
	Updating of OR time	Final OR schedule is created
	Arrival of emergency patients	Patients requiring emergency operation are sent for procedure
	Cancellation of scheduled operations by emergency arrivals	Emergency patients requiring immediate operation replace previously scheduled patients in the OR schedule
	Cancellation of scheduled operations by inpatients	Inpatients requiring surgery replace previously scheduled patients in the OR schedule
	Cancellation of scheduled operations	Scheduled elective patients being deemed unfit for surgery are removed from the OR schedule
	Rescheduling of cancelled operations	Patients who are still waiting for operation after surgery was cancelled are identified, and hospital resources are reserved
	Surgical procedures	Operation is performed, during which time patients have access to operating theatre resources
	Discharge from hospital	Patients are prepared for post-operative care at home or in rehabilitation or community facilities
Surgical service	Audit of wait lists	Names of patients who die while waiting for the operation are removed from surgical waiting lists
	Allocation of consultation slots to PAC	Updates consultation slot allocation to PAC for upcoming weeks
	Allocation of appointment and OR slots to surgeons	Slots are allocated to surgeons according to duty rotation and vacation schedules

These three features extend the Mealy-Moore state machine concept, in which a system never can be in two states concurrently, and the state machine can be decomposed only into sequential sub-states [47]. The Statecharts formalism overcomes this limitation allowing parallel (concurrent) sub-states that become active or inactive together with the state in which they are nested. Combined with hierarchy and parallelism, event broadcasting offers a convenient way to coordinate the transitions within concurrent states in an asynchronous fashion.

The Statecharts defines four kinds of events: generated by asynchronous processes, generated by an action within a machine, generated by the change in value of an attribute, and generated by regular time advances. By allowing probability distributions of time to event, the Statecharts are also capable of capturing the stochastic behavior of a reactive system [36].

The semantics of Statecharts is amenable to mathematical analysis [62], and a simulation engine can execute statecharts, similar to a program code. A full definition of the Statecharts syntax is beyond the scope of this article, and we refer the reader to the original article [33].

5 A Statecharts-based model

We employed the Statecharts language to develop specifications for a discrete-event model of the peri-operative process for surgical coronary revascularization [49–52]. For this, we mapped the clinical and operational activities of surgical care in the British Columbia hospital and organized the information in a way that was suitable for constructing statecharts. The mapping results included a narrative describing patient progress from first presentation with symptoms of coronary artery disease through care steps [52], a flowchart showing an assemblage of consecutive care activities, described in detail elsewhere [53], a list of states describing clinical and operational actions within key care activities, and a list of transition specifications controlling the progress of patients through the states.

Using the Statecharts concepts of hierarchy (nested states), parallelism (concurrent active states), and event broadcasting (coordinated transitions across machines), we constructed a discrete-event simulation model in which the progress of individual patients was modeled as a series of updates in patient records. These updates are driven by events or by changes in data tables generated by parallel finite-state machines representing concurrent clinical and managerial activities. For each machine, we defined states, transitions between the states, events triggering the transitions, conditions controlling the transitions, actions associated with the transitions, and temporal logic of events' occurrence.

We modelled three care paths that patients with coronary artery disease are likely to experience according to initial presentation and subsequent decisions leading to surgery: elective, inpatient, and emergency. The elective path applies to patients for whom surgical consultation and subsequent operation can be safely delayed. The inpatient path applies to patients admitted to hospital from the catheterization laboratory when urgent surgical assessment is necessary. The emergency path applies to patients requiring immediate surgical intervention.

Through the simulation run, events may occur either at regular time points or asynchronously. For example, the event that activates the machine "Scheduling OR time" is synchronized with weekly clock, whereas the event that triggers the placement of a patient record on the surgical wait list is generated by the machine "Outpatient appointments" at the completion of a consultation. The machines react to internal and external events by broadcasting other events, by calling algorithmic functions, or by updating internal queues and data stores similar to what was described elsewhere [36]. Some of these updates trigger actions across several states or machines. The sequence of events generated asynchronously by concurrent machines determines the delivery of care to the population of modeled patients.

For example, using notions of parallelism and event broadcasting, we modelled the availability of three surgeons for consultations, scheduled operations, and on-call duties according to the rotation and vacation schedules in the service, Fig. 1. We did not impose the distribution of clinic and OR slots by individual surgeons, which is usually determined by the statistical analysis, but thoroughly specified interactions between processes that constantly adjust an initial allocation of the slots according to changes in case volume and mix. Complete model documentation, including the Statecharts specifications, tables describing machines, their functionality in the model, events, their source and destination, is available from the authors.

6 Policy analysis using simulations

The analysis of policy alternatives involves statistical comparison of performance measures across intervention groups to quantify the effects of policy changes. For example, one common performance indicator, the probability of seeing a specialist within a certain time after referral, is derived from observed times to appointment using the Kaplan-Meier method [54]. The appointment probabilities for several scheduling methods are then compared statistically by the log-rank test to identify the method with the shortest time to appointment [55]. Similarly, data from simulation experiments can be used for performance evaluation of the modeled system. The use of simulations for evaluating healthcare policy has two premises: first, that the collective experience of simulated individual care paths can be used to represent the delivery of health services to a patient population, and second, that simulation experiments produce the care paths that are likely under various policies [56].

A simulation experiment involves running the model with inputs that represent policy alternatives and those

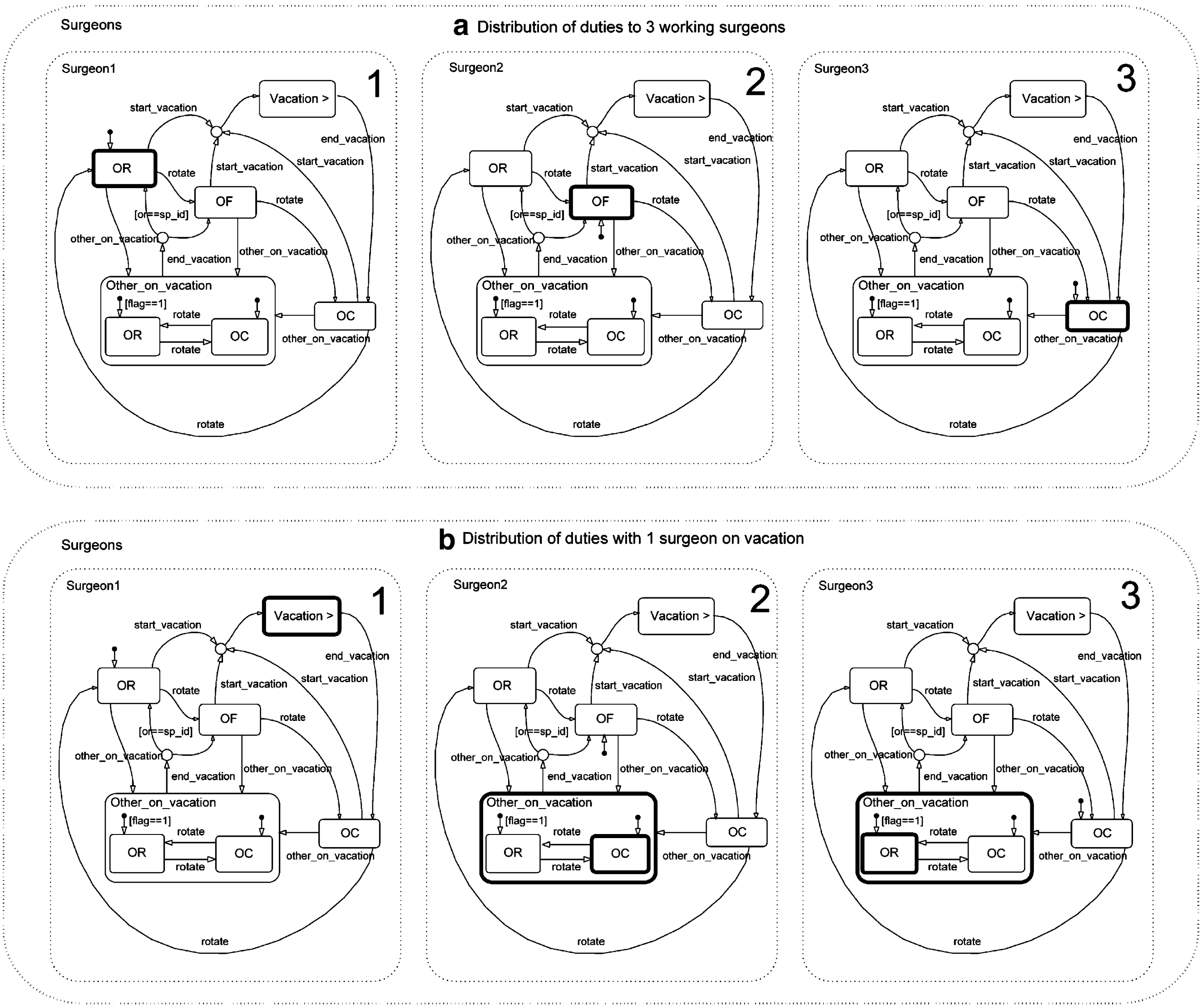

Fig. 1 Statecharts describing the availability of three surgeons in regular weeks (**a**) and in weeks where one surgeon takes vacation (**b**). Event *rotate* triggers transitions between duties (**a**). Event *start_vacation* triggers transitions between duties and the vacation state (**b**). Once one surgeon is on vacation, two remaining surgeons alternate between scheduled surgeries (*OR*) and on-call duties (*OC*) until event *end_vacation* occurs

having an effect on system performance without being affected by policy change. The components of patient-flow models usually include methods of organizing and delivering specific activities and parameters of organizational arrangements (e.g., frequency, timing, duration, occupational mixes, setting). During the simulation run, patient records are stored in internal queues, such as appointment lists. Internal queues are dynamic tables with fields containing patient attributes that are updated by state machines representing the modeled activities; for example, completion of an outpatient clinic appointment with the surgeon causes removal of patient record from the related internal queue. External data stores capture the occurrence and timing of simulation events, such as registrations and cancellations; for example, a data store of wait list registrations has fields such as the patient's unique identifier, the registration date, and the priority for treatment. As with the internal queues, state machines update the data stores in reaction to events generated by other machines. After a simulation run, individual patient paths are re-created by importing records from the data stores into a relational database and then linking the data stores by the combination of run and patient identifiers uniquely specifies all rows in each data store. Study outcomes are then computed from values taken from fields in the linked data stores. For example, time from referral to appointment is computed as the number of Sundays between the registration date and appointment date.

Statecharts facilitate the representation of policy changes that target interaction among processes in care delivery. In a previous analysis, we used Statecharts specifications to compare policies for scheduling outpatient clinic appointments in a setting where the availability of surgeons for appointments depends on other activities [57]. Scheduling clinic appointments is a common element of planning surgeons' activities within a clinical practice. The schedule determines the appointment date for the consultation preceding an operation, and the length of time between referral and appointment depends on the number of referrals, the availability of surgeons, and the method for scheduling appointments [58]. Pooling referrals on a single waiting list and scheduling appointments with the first available surgeon, not necessarily the referral surgeon, had been recommended as a way of reducing patient waiting times for the consultation appointment [59]. However, the impact of such a scheduling method on times to appointment and to surgery was not well understood. Using simulation experiments, we found that pooling referrals and scheduling appointments with the first available surgeon did indeed reduce the time to appointment [57]. However, the evidence also suggested that such an intervention would result in increased waiting times to surgery for less-urgent patients unless surgical capacity was increased.

7 Discussion

Computer simulation of patient flow has been suggested as a method to assess the effects of changes in the organization and management of surgical care [3, 4]. Despite the development of a variety of approaches, little research is available on the appropriateness of modeling techniques. In this paper we have described the Statecharts approach to constructing discrete-event simulation models of the peri-operative process.

Other researchers have suggested that the redesign of health services may involve description of the complexity of existing care processes, with attention to the implications for care providers and hospital staff [60]. We argue that viewing the delivery of surgical care as a reactive system of parallel activities is a powerful approach for identifying likely responses to changes in the peri-operative process. Our argument has two premises: (1) that the complexity of the peri-operative process stems from its reactivity [46] and (2) that the most appropriate modeling approach will capture the behavioral aspects of care delivery when policy changes target the interactions of clinical and managerial activities.

For example, pre-booking the operation date at the time of decision to operate has been suggested as an alternative method for scheduling elective surgery in the UK National Health Service [61]. Therefore, assessing the impacts of the proposed change using a simulation study entails a description of the interaction between specialists' and hospitals' schedules. In the pooled-list simulation study, we used the Statecharts' notions of parallelism and event broadcasting to represent the availability of surgeons for appointments, scheduled operations and on-call duties.

We conclude that the visual formalism of Statecharts enables the representation of surgical care delivery as a reactive system of concurrent activities by providing rigorous specification of permissible sequences of events, conditions, and actions and the temporal logic of events generated by these activities.

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