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DESIGNING EFFECTIVE HYBRIDIZATION FOR WHOLE SYSTEM MODELING AND SIMULATION IN HEALTHCARE

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ABSTRACT

Wider healthcare provision is typically reliant on a complex choreography of service providers and associated stakeholders. Ambulatory, accident & emergency (A&E), primary care and other services need to be able to react to a number of changes, including demographic and associated funding pressures. Combining Modeling and Simulation (M&S) methods as part of a hybrid simulation is better able to support diverse stakeholder perspectives and more importantly provide a means to collaboratively understand the wider system, offer system insights and robust assumptions across models and calibrate time-specific scenarios as model inputs. A collaborative hybridization approach is required at the outset in order to fully benefit from distinct M&S approaches. This paper presents a hybrid M&S project for non-elective health provision across the wider system. A number of "software" design methods are latterly presented as a means to support requirement gathering, model design and subsequent data flow and simulation integration.

1 INTRODUCTION

Whilst hybrid simulation has been around for some time, recent renewed interest is motivating a revisiting of issues around conceptual understanding, collaborative modelling and interoperation mechanisms. It has been argued that hybridization requires an additional focus on conceptual modelling (Zulkepli & Eldabi 2015). However, little focus has been paid to the collaborative nature of designing, building and running such hybrid environments. In light of recent technological innovation and challenges associated with collaborative work, new approaches are required to support key modelling processes. Collaborative hybridization methods are required at the outset in order to fully benefit from distinctive M&S approaches and more importantly result in more effective simulation outcomes. In response to modelling and simulation project work carried over the course of several months at a UK National Health Service (NHS) Clinical Commissioning Group (CCG), a number of "software" design methods are presented as a means to support requirements gathering, model design and subsequent data flow and simulation integration. This paper presents a hybrid M&S project for non-elective health provision across the wider service system.

Healthcare has been a popular home for hybrid simulation (Gao et al. 2014; Onggo 2014; Viana 2014; Fakhimi et al. 2015), also providing opportunities to explore wider system issues (Brailsford et al. 2010). Recent literature has typically focused on specific case studies, clearly demonstrating practical viability of the approach. Fewer publications however have explored the modelling process, especially when designing across organizational boundaries. This paper explores the use of software design techniques as a means to support organizational boundary crossing hybridization.

The remainder of the paper is organized as follows. Section two presents literature on the use of software design in support modeling and simulation. Section three summarizes the design science research method, articulating the links between the commercial healthcare project undertaken and the research presented here. Section four describes our case study in non-elective healthcare. In response, a number of Unified Modeling Language (UML) software modelling approaches are described in section five as a means to more effectively support collaborative hybrid modelling. Section six concludes the paper, summarizing the research, highlighting contribution and discussing future research.

2 BACKGROUND ON MODEL OF MODELING PROCESS

Collaborative modelling has a long academic and industrial history. Richardson and Andersen describe five essential roles that should be present when group model building: 1) the facilitator, 2) the modeler/ reflector, 4) the process coach and 4) the recorder and the gatekeeper (Richardson & Andersen 1995). Software modeling, such as UML (Rumbaugh et al. 2004), has attempted to support an range of roles and stakeholder groups, typically with more specific diagrammatic approaches. However, questions of readability across diverse groups have been raised (Petre 2013). Unsurprisingly, within the simulation community, modeling approaches have tended to focus on the underlying paradigm and not on the process of model development. Discrete Event System Specification (DEVS) is one example, providing a discrete-event formalism (Zeigler 1987). Similar readability concerns about DEVS models have been investigated using UML Activity diagrams (Özmen & Nutaro 2015). More recently, software models have also been used as a basis for the simulation itself. Collaboratively building a simulation environment using different modeling paradigms and models requires more consideration of the design process however.

UML itself is widely used in the software engineering industry, emerging from a number of competing notations in the early 1990's. A range of diagram types exist, from more user oriented use-cases to software oriented sequence diagrams. Traceability between diagrams has always been an important aspect of UML. SysML was added as a UML profile including both a subset and extension to its core. It has gained some interest in the simulation community due in part to its focus on engineering design with more specific requirement definition and the addition of constraints on system elements (or blocks). Unsurprisingly, with additional rule definition, SysML has been used as basis to auto generate simulation models (Huang et al. 2007).

Software models have also been used as a basis for simulation (other than SysML). The complexity of healthcare is often viewed as a system of systems (Zeigler 2014). Consequently, synchronization between systems needs to be exposed in models and simulations. Kim and Yeo (2014) used a range of UML models to generate Java based hybrid simulation. Activity diagrams were been used to define synchronization points between models. Business process modeling notation (BPMN) typically takes a higher-level, more service oriented view of a wider system. BPMN has also been used in simulation, both in student DES healthcare projects (Taylor et al. 2014) and as a possible means to promote wider use of agent based modelling (Onggo & Karpat 2011). It is apparent from much of the literature that in order to build simulations using UML or BPMN a number of constraints exist: 1) Specific modeling patterns must be followed, 2) considerable configuration data must be provided and 3) simulation functionality is varied across tools. Furthermore, literature in this area fails to consider the more human, collaborative nature of hybrid simulation, an important initial motivation for using software modeling tools in the first place.

3 AN INDUSTRY-AS-LABORATORY DESIGN SCIENCE RESEARCH APPROACH

This research follows design science research guidelines (Hevner et al. 2004) which promote both theoretical contribution alongside more practical design outputs. Typical contributions of a design science research project are one or more artefacts, taking the form of constructs, models, methods and/or instantiation in March and Smith (1995) parlance. This research has explored how software modelling is able to more effectively support the simulation hybridization process, more specifically the collaborative nature of such projects. An "industry-as-laboratory" research paradigm enables "researchers to identify problems through close involvement with industrial projects, and create and evaluate solutions in an almost indivisible research activity" (Potts 1993 p.20). This replication of industrial problems requires a research method that can be deployed to (a) solve such specific problems, (b) support both process and artifact analysis and (c) allow iterative, interpretive approaches to upfront hypothesis.

This project and allied research produced a rich set of artefacts (a number of which are presented below) and included evidence logging, contracts, presentations and emails; as well as the simulation models and resulting simulation runs. When considering artefacts it is worth noting the difference between project and research artefacts. Project artefacts are generated over the course of the project (including the core modelling and simulation). Research artefacts then follow in response the project itself and extant project data. The description of how software modelling can be applied is undertaken after the live project in order to address specific collaborative needs that were witnessed earlier.

Continuing on from project-based iterative simulation and modelling processes, an additional reflective iteration is appended to the project. Extant data and project records are analyzed in order to design a number of software models that more effectively support hybrid simulation projects of this type. Grounding outputs in the project data is able to validate artefacts and support their use. However, further utilization on additional projects is required to further validate effectiveness.

4 WHOLE SYSTEM HEALTHCARE MODELLING

4.1 Live Project Description

The project detailed in part in this paper in an ongoing project carried out over a number of months. The project team brought together two simulation companies (SIMUL8 and WSP) and Brunel University London. Partners operated as part of the Cumberland Initiative (http://cumberland-initiative.org/). The project was initiated by a UK NHS CCG who specified a number of strategies they wished to explore and simulate impact. Importantly, the project was tasked with the non-elective care and the associated wider system of services before and after the accident and emergency (A&E) envelopment. SIMUL8 focused on the discrete-event simulation (DES) modelling and WSP on system dynamics (SD). Brunel University London led the project and provided additional research into data analysis and the hybridization process. The process undertaken is detailed at a high level in table 1.

Table 1: The Collaborative Hybridization Process.

Process	**Description**
Scoping	The project was scoped over three sequential steps: 1) Contract negotiation, 2) a kick-off meeting and 3) scoping documentation. The central focus of scoping was on specific simulation requirements and user strategy explorations.
Evidence Gathering	Evidence is gathered from the outset, including organizational topology, key-stakeholders and possible sources of information.
Individual Modelling	Each modelling team develops specific models addressing aforementioned simulation requirements.
Collaborative Modelling	After iterating through a number of model runs, connection between models is designed.
Scenario Execution (i)	A number of scenarios are executed and associated dashboards populated. Baseline data is presented in more detail.
Demonstration	Results are presented to the client (with initial findings).
Interim Review	The approach and initial results are reviewed by an external expert.
Acceptance Testing	More detailed results are presented to the client (alongside a detailed model walkthrough and demonstration). Baseline inputs and model assumption are also presented.
Scenario Execution (ii)	A final number of model runs are carried out.
Reporting	Reports are produced and dashboards populated.
Final Review	The final reporting is reviewed by an external expert.

Three key transitions described in table 1 are also revisited later – for software design consideration. First of these is the scoping-evidence gathering steps where all team members require a clear understanding of the aims, objectives and key stakeholder groups. Implied in this understanding is knowledge of who and when additional data is being collected. Interviews with these key stakeholders are subsequently able to provide evidence for model elements and baseline configuration. Secondly, the individual-collaborative modeling steps require a means to both understand macro state transitions, associated system data at these points and mechanisms for transfer between models. Finally, a more detailed design for data transfer is needed, covering the software components involved and associated data standards. Before addressing these transitions, the respective models and simulations are presented.

4.2 Demographic and Strategic Interventions

The baseline demand projections used in the system dynamic modelling were based on both demographic data and prevalence data to develop a series of demand drivers for key population cohorts. A series of stakeholder interviews were held to identify priorities for strategic system change. These included interviews with service commissioners, service providers and clinicians. The objectives of the stakeholder engagement process were to: 1) Understand what stakeholders in the wider system saw as the principal issues having an impact on the core unplanned care pathway, 2) identify known/ expected system changes likely to have an impact on the core pathway in the future, 3) explore potential service changes with the potential to improve performance in the unplanned care pathway and 4) enable intelligence and insight from one source to be triangulated across the system.

The system dynamics model was subsequently developed to simulate the impact of both the expected changes in baseline demand and the identified strategic service changes on the performance of the system, and in particular on demand for unplanned care. Applying the strategic service changes resulted in changes to the simulated level of demand for unplanned care. The variation in demand was simulated over time in the model outputs. This provided the basis for selecting alternative sets of input data to the operational model, based on (see figures 1):

- Strategic service changes selected
- Assumptions made relating to the scale and timing of the implementation of each strategic service change
- Time points at which the resulting demand was modelled

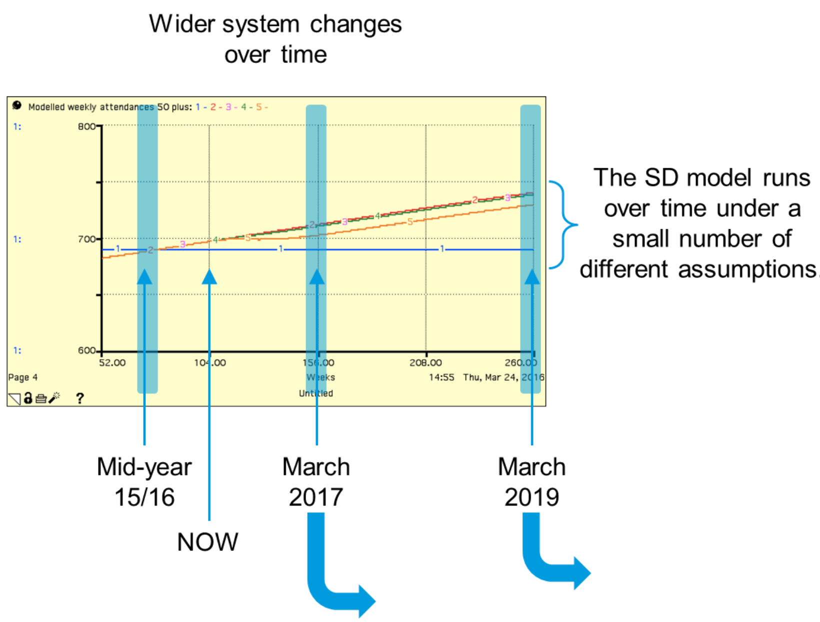

Figure 1: An example of SD modeling outputs.

Figure 2 is an example of SD output, presenting A&E attendances (after demographic and strategic changes) for a range of patient groups.

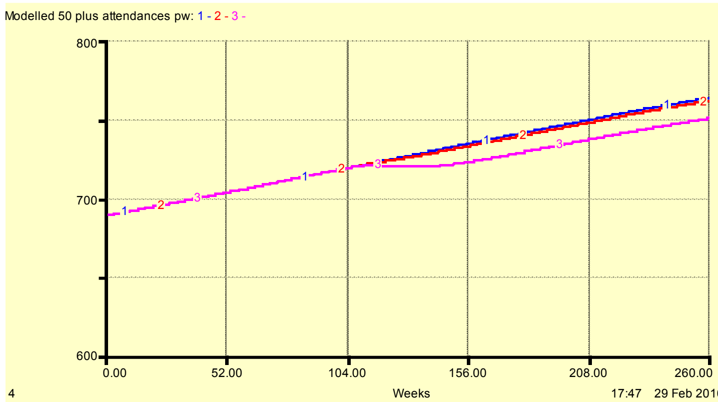

Figure 2: An example SD results.

4.3 Modelling Impact at an Operational Level

The DES was built to represent the wider system across the care system. Importantly, model elements were used to represent possible strategic change scenarios – accepting data from the SD model. Figure 3 presents a snippet of the DES model. After baseline testing a number of scenarios were explored, including bed numbers, care home support, ambulatory services and additional primary care.

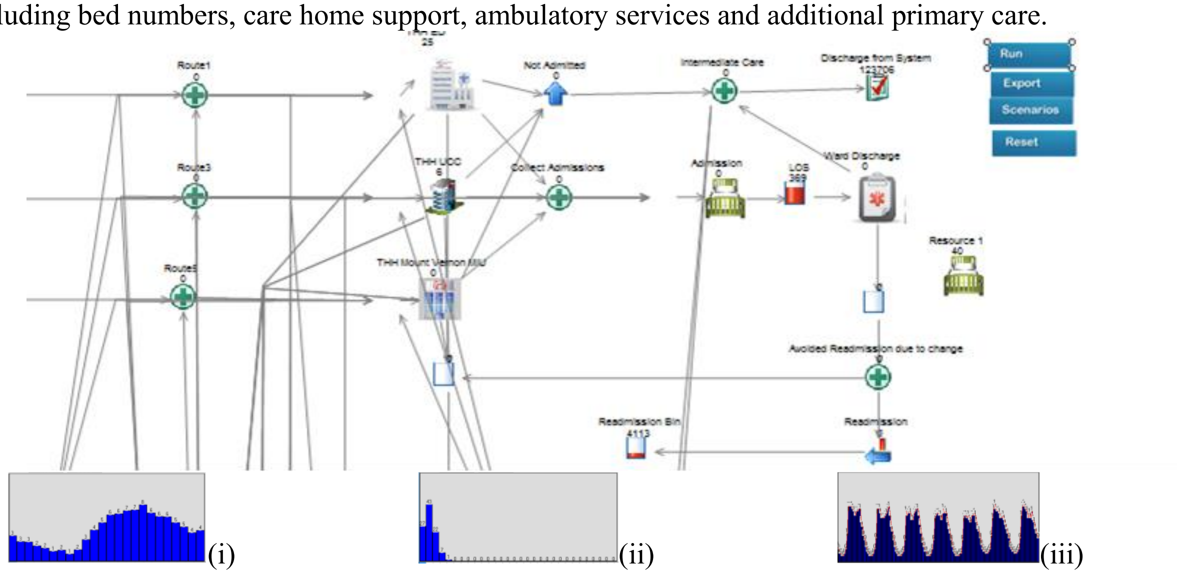

Figure 3: The DES Model with example distributions.

SIMUL8 software was used to build a DES. The simulation mapped patient activity for one year through urgent care services. It used transactional data from the Health and Social Care Information Centre (http://www.hscic.gov.uk/) to accurately build a baseline of flow through these different services. Data was segregated by patient age, arrival method and arrival time to build distributions of arrival, routing and length of stay for patients in different services, including (i) discharge by hour, (ii) length of stay by hour and (iii) pediatric arrival. These separate distributions and routing patterns were tested against baseline data to ensure accuracy. Once accurate baseline were established, pre-defined changes were tested in the software. These changes typically explored the impact of more patients using alternative services. The fine grained segmentation of data enabled testing of changes more precisely, especially when looking at specific demographic impacts from SD modeling.

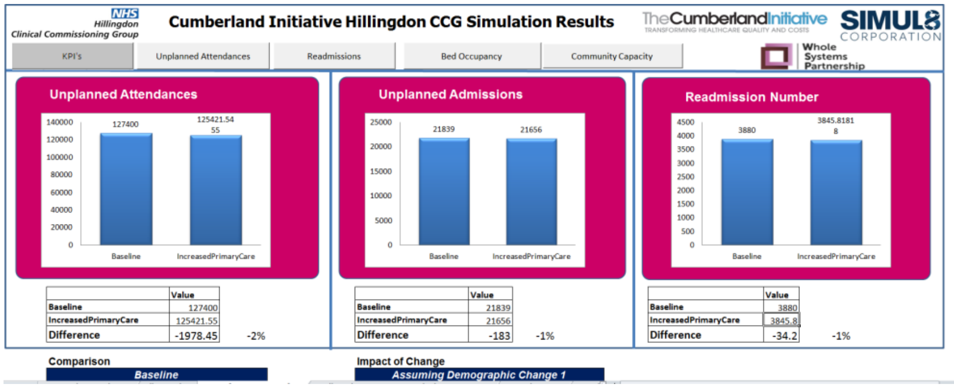

Figure 4: A snapshot of the DES Dashboard.

Co-ordination of data is critical in collaborative modelling, including expert input from interviews and model outputs. Uncovering relevant data drives connectivity between modeling activities and the models themselves.

4.4 Connectivity Between Models

How DES and SD models deal with time differs, and it was therefore important to consider carefully the nature of data exchange between the two modelling approaches. In a DES model the discrete entities pass through the model under a single set of assumptions from end to end of the modelled pathway. In this case the DES model has simulated the pathway from attendance at A&E to discharge from the hospital (with many runs) - reflecting the passage of time across the pathway. However, initial conditions change over time and the DES model is 'reset' and run are executed with a new set of conditions or, as in this case with the link to the SD model. Conditions at new point in time are informed by longer term strategic modelling using SD.

An SD model is a continuous simulation, and in this instance the model simulates changes in what are effectively the underlying baseline assumptions that can inform the DES model. For example, demographic driver are modelled that change incrementally over time alongside changes in the capacity in a number of pertinent 'out-of-hospital' services. When an SD model is run on several occasions this is typically under different baseline assumptions rather than as a result of different random variables within the run of the model (although this is possible within an SD model it is not how we have chosen to model in this case).

Each time step within an SD model represents a new set of initial conditions, whilst each time step in a DES model reflects the consequence of a cumulative, distribution based set of discrete entity 'decisions' based on a single set of initial conditions which are run multiple times. This means that pausing the SD model, or simply extracting a set of data outputs at particular points in the SD simulation (which in this case has been run over a 5 year period) provides an alternative set of initial conditions for the DES model to use, along with other 'internal' options that impact on the initial conditions within the bounds of the DES model. Both models use the same original baseline assumptions (which is time 0 in the SD model, or the baseline run for the DES model). The SD model is then used to derive new baseline assumptions for the DES model at two significant points in time, one at the end of a period over which proposed changes in the wider environment have been simulated, and one at a more distant point in the future to test for sustainability of the proposed solutions.

5 SOFTWARE MODELS FOR HYBRIDIZATION

A number of software modelling approaches can be utilized in support of the hybrid modelling process, specifically: 1) Initial scoping of the modelling requirements, 2) design time inter-operation between models and finally 3) practical inter-operation and data flows. Software models are able to facilitate communication between software (model) developers and provide clearly defined interfaces in terms of context, events and data. Summary models are included in this paper to clearly present their merit.

5.1 Scoping the Project

A key element of a project kick-off is understanding the scope of the project. Stakeholders associated with each requirement need to be identified, both to understand their activities as part of the wider system and also to plan follow up information gathering interviews. Interviews provide knowledge required to understand the system and also identify sources of additional data for analysis – including larger on-line data sets. The UML model that best support these scoping activities is the use case diagram. Actor inheritance can be used to identify specific stakeholders and their organizational units. Figure 5 provides a motivating example depicting one requirement and one organization. Each use case is able to define a specific simulation requirement or strategic idea to explore, e.g. reducing unplanned attendances at accident and emergency. Actors can be annotated with data supplied directly or from their systems.

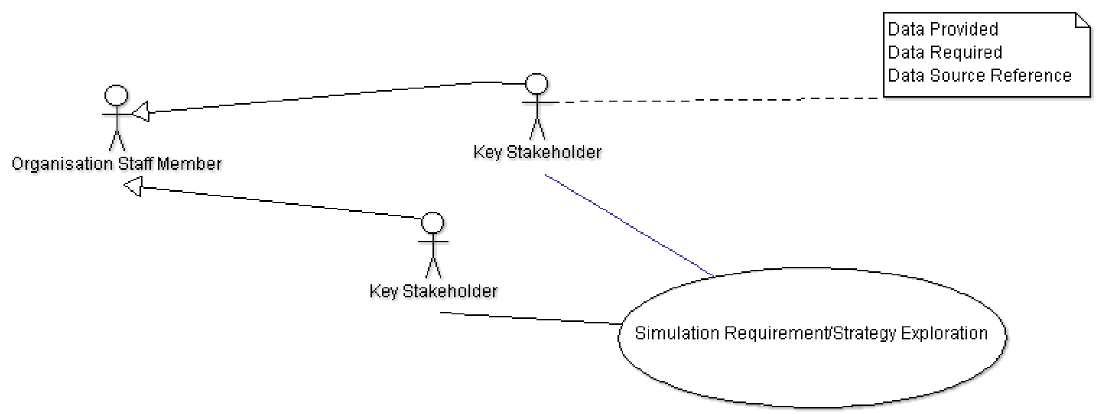

Figure 5: Use Case Modelling of project scope.

Use case narratives are then able to define the elements of service delivery for a specific organizational unit as steps. Importantly, data (acquired or required) or associated sources (e.g. data warehouses of flow data) are also detailed in the narrative alongside a particular stakeholder or in the step definition. Independent M&S activities follow with service elements defined that supplement models where appropriate. An example of strategy would be to test admission avoidance and discharge strategies.

5.2 Designing Connectivity in the Models

Designing connectivity is central to hybrid simulation and typically relies on the state of a system at a particular time (as shown in figure 1 depicting three points in time). Behavioral state machine diagrams are able to link demographic data that includes modeled strategy impact at particular points in time with more fine grained simulated whole system operation. The former being the SD model, the later the DES model. Each model or model output represents granular state changes, although less concrete in continuous SD form where outputs are representative of interesting change points or events. The modeling of state transition across models begins an understanding of how inter-operation can occur, including semantic integration. Connection states allows the designer to focus more on these specific points when interoperability is required. Others have used activity diagram to more fully define the underlying system and the connection between models. Our approach leaves this definition within the use-case narrative and instead focuses on each model state (model m1 and m2 in figure 6) and then on synchronization states (*). Annotation is added to synchronization state, model connection points, detailing data to be transferred and reasoning for transfer at this point. Progressing from use-cases to state machine diagrams is not typical in software projects, but more natural when designing alongside simulation modeling within commercial simulation packages or software. UML is being used to supplement M&S with diagrams that support collaborative working and decision making.

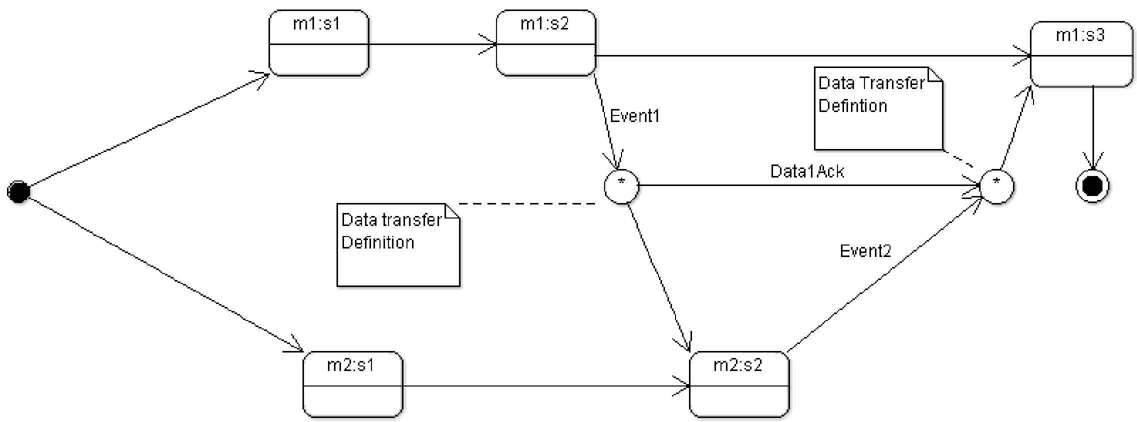

Figure 6: Modelling interaction points between simulations (including time and state).

Although a relatively simplistic state-transition is presented, it is important to clearly articulate states across the hybrid simulation environment and more specifically for inter-model synchronization (including events that drive the synchronization – e.g. Event1 and 2). State annotation can be used to describe a particular state such as temporal or content references. It is important to note that the state machine diagram presented is a holistic view encompassing all of the modeling environment and consequently documents states and interaction involving all models. State transition labels are able to detail events triggering synchronization between models in additional to more standard intra-model transitions. An subset of SD to DES data transfer is depicted in Table 2 – noting that this transfer takes place at specific event (3 time events in the case of this reported project).

Table 2: Example properties from SD-DES interaction.

Property	**Value**
Modelled weekly attendance after interventions 5-17	405
Modelled weekly attendance 18-49	995
Modelled weekly attendance 50+	667
Rapid Response Caseload	7.4
Bed Occupancy	19.4
Over 65 discharges	155

5.3 Designing Data Flows Between Models

Sequence Diagrams are able to model messaging between objects. Objects of interest in hybridization design are the specific simulation models themselves and components that enable connectivity. Each unique connection point can be modeled, designing the specific messaging that needs to take place.

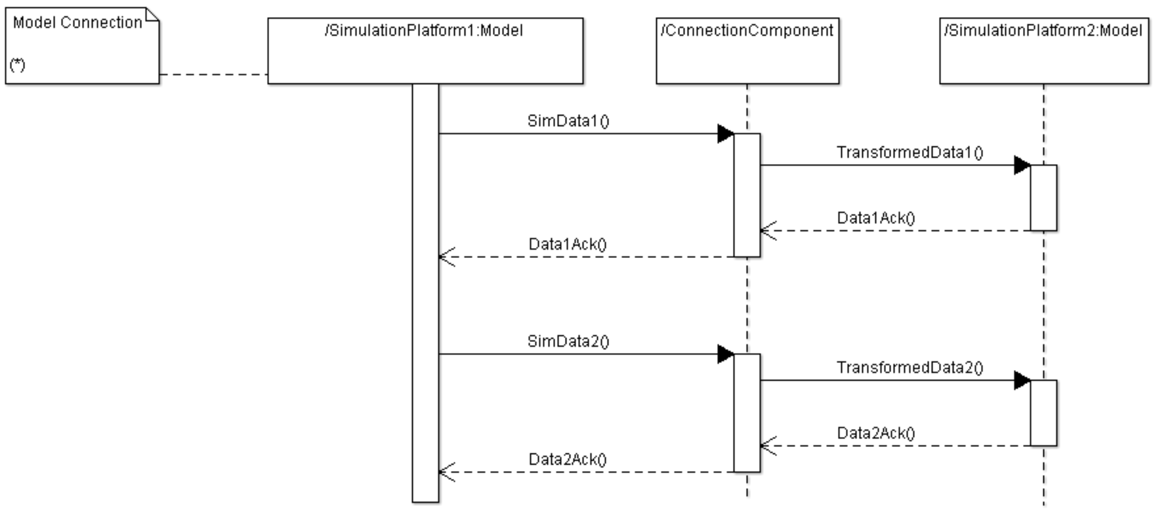

Figure 7: Modelling data flows between models.

The sequence diagram (figure 7) models the synchronization points (*) and design of the *ConnectionComponent,* articulating whether data translation functionality is placed within the simulation model sending data (*sender transformation*) or receiving data (*receiver transformation*). If neither of these approaches are possible an interface component is needed (*component transformation*). The messaging (*SimData* and *TransformedData*) requirements for each simulation define the transformation process taking place at a particular state in the sender model (Figure 6). Traceability must be maintained in the UML modelling between the connection and the event (*).

6 CONCLUSION

Hybrid simulation of healthcare system of systems is able to explore the impact of strategic change at a number of levels. This does however require additional design consideration when modeling is carried out as part of a collaborative endeavor. Common throughout the hybridization process presented is a focus on data, from its initial sourcing to later stages of inter-model data transformation. After presenting the DES and SD modeling a software oriented design approach is presented that supports M&S undertaken across organizational boundaries. Software models are used as a means to support better communication between technical stakeholder groups that often have different modelling perspectives – thus improving respective simulation models and their connectivity. UML diagrams are proposed as a means to capture project scope through inter-model data transfer. Importantly, the combination of SD and DES modeling is able to test strategic service changes and resulting impact on the level of demand for unplanned care. In summary, three UML modeling approaches are presented that sit alongside core M&S that are able to support key stages in the hybrid modeling process:

Use Cases *scope the project in order to begin the individual M&S activities.*
M&S *activities are carried out by one or more modelers, in response to the Use Cases.*

State Machine Diagrams *describe points when models need to inter-connect.*
Sequence Diagrams *identify the connectivity code and messaging required to connect each model.*

Consistency and traceability are important, both between UML models (e.g. each use case strategy having a modelled interaction) and across UML and simulation models (e.g. precise event processing). Additional design work is envisaged to fully define the inter-model data transfers that are needed for hybrid simulation of complex healthcare system of systems. In particular, more configurable semantic interoperability is needed to better support specific model, data and simulation platform requirement.

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