

DEVELOPING HYBRID KIDNEY CARE MODELS WITH FACILITATED MODELLING

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ABSTRACT

This paper presents a simulation modelling study aimed at supporting capacity planning of kidney replacement therapy services offered to patients at different stages of kidney failure. The model consists of a combined discrete-event simulation (DES) and system dynamics (SD) model, representing two different aspects of kidney care. The SD model represents the demand for kidney care by modelling disease progression in patients over time, whereas the DES models the provision of care including kidney transplantation and different types of dialysis offered either in hospital or at home. A facilitated modelling approach is adopted to engage with a range of stakeholders representing kidney care services to ensure the development of a relevant and representative model. To the best of our knowledge, this is the first facilitated modelling study of a combined (hybrid) simulation presented in the literature. We present the approach, followed by reflections and future work.

Keywords: Facilitated simulation, kidney care, health services, system dynamics, discrete-event simulation, hybrid simulation.

1 INTRODUCTION

Chronic kidney disease (CKD) is a long-term condition, where patients' kidneys become increasingly less able to filter waste from the blood. This progressively worsening kidney function is classified from stage 1 to stage 5. Kidney replacement therapies (KRT) are treatments given to people with CKD which has progressed to kidney failure, replacing their normal kidney functions. The main types of KRT are dialysis (at home or in-centre) and kidney transplantation (from a living or deceased donor). Nearly 71,000 adult patients were receiving KRT for end stage kidney disease at the end of 2022, among which 56.2% were transplant recipients (UK Renal Registry 2024). Patients can also receive conservative care to manage symptoms while maintaining the quality of life, especially those whose frailty suggests that KRT may be counterproductive.

Dialysis is expensive, with costs estimated at around £36,000 per patient per year for in-centre treatment, although mortality remains high, and quality of life remains significantly impaired. Dialysis at home is cheaper (between £17,000 and £24,000 per patient per year), and it can be associated with

better quality of life, but the uptake of this option is variable. Kidney transplantation provides better quality and length of life at reduced cost but is not possible when the peri-operative mortality risk is too high, and the availability of donor organs remains a rate-limiting step. The number of patients on in-centre dialysis has been inexorably rising in the UK for several decades now (UK Renal Registry 2024). The growth curbed during COVID-19, although this is likely due to high mortality rates from COVID-19, so estimates foresee the growth in demand for dialysis to continue (UK Renal Registry 2024).

These issues make the management of KRT services challenging, with an urgent need to minimise future demand for in-centre dialysis, along with the associated ill-health, environmental cost and healthcare expenditure. This highlights the need for the optimisation of transplantation and dialysis-at-home services, as well as reducing the progression of CKD to kidney failure. In addition, predicting the increased capacity needed for unavoidable in-centre dialysis can support decisions for new dialysis units to be built and staffed. Achieving this will require realistic and evidenced estimates of the impact of investments in different possible strategies, taking population changes in size, ethnicity and age into account. This also calls for an approach that integrates primary, secondary and tertiary care of patients with kidney disease within the UK National Health Service (NHS), ensuring appropriate co-ordination across the different NHS organisations and structures.

The aim of this paper is to present the simulation modelling study undertaken to support capacity planning decisions for KRT services. This study is undertaken as a collaboration between The Strategy Unit (SU), Nottingham Trent University and Midlands Kidney Network (MKN). The model is intended to be used by the Midlands Kidney Network to support capacity planning decisions at a centre- and unit- level, as well as by other NHS kidney networks and KRT providers in England. The model combines two modelling approaches, discrete-event simulation (DES) and system dynamics (SD), to ensure that the kidney care system is represented effectively. The SD model represents the demand for kidney care by modelling disease progression in patients over time, and the DES model represents the provision of care services including kidney transplantation and different types of dialysis, to cater for future patient demand. We adopt a facilitated modelling approach to engage with a diverse group of stakeholders involved in kidney care services to ensure that a relevant and representative model is developed that can support decisions and future capacity planning for the NHS.

The contribution of this paper is twofold. First, the model developed extends existing kidney care simulation models as it provides a comprehensive and more accurate representation of the kidney care provision systems and current care pathways in the DES model, including diversion to conservative care, pre-emptive transplant and home haemodialysis (HHD). Furthermore, demand for kidney care is more accurately represented as it is generated by a separate model component (the SD model) that tracks disease progression in the population over long time. Such a model that operates at both service provision and demand levels for kidney care is not available in the existing literature. Secondly, it contributes towards the facilitated modelling methodology by presenting a novel study that adopts a facilitated approach for developing a combined (hybrid) simulation study. To the best of our knowledge, this is the first facilitated modelling study of hybrid simulation presented in the literature.

The outline of the paper is as follows. Section 2 briefly reviews existing models on kidney care and the state of art in facilitated hybrid simulation modelling. Section 3 explains the methods and the novel facilitated modelling process adopted. Section 4 presents the preliminary SD and DES models developed, while section 5 concludes the paper.

2 BACKGROUND ON KIDNEY CARE MODELLING

2.1 Kidney Care Modelling

A range of approaches have been used to model both the disease progression of CKD and the demand for KRT in the current literature.

An early DES was previously developed to model future demand for KRT in England (Roderick et al. 2004). The model utilised prevalence data, acceptance rates, survival rates, and transitions between haemodialysis (HD) and peritoneal dialysis (PD) treatment modalities. It used national population and mortality statistics, literature, and data from the UK Renal Registry and UK Transplant to assess unmet

needs, demographic changes, and the impact of Type 2 diabetes on patient survival and transplant availability. An adapted version of the model was used in 2007 to inform plans for future kidney care services in the West Midlands (Warwick Business School 2007). These models and patient pathways are now outdated and were created in a software which is no longer available. The “Inside CKD” programme (Chertow et al. 2024) used a microsimulation model to project the CKD prevalence and costs over time, with country-specific analyses based on diagnosis rates, disease progression, comorbidities, treatment and mortality. A UK-based case study predicted 9.2 million CKD cases over 6 years to 2027, with a 5% rise in costs for diagnosed CKD and KRT (Tangri et al., 2023). Allen et al. (2020) developed a DES to support the organisation of dialysis services during the COVID-19 pandemic in the South of England.

SD models are useful in shaping health policy and representing population dynamics. Ansah et al. (2021) used an SD model to investigate the impact of interventions on the prevalence of CKD, end stage kidney disease patients needing dialysis, and the cost of dialysis in Singapore up to 2040. With projected increases in CKD and dialysis, the cost of dialysis care was projected to more than double in the base case. The interventions investigated showed that significant savings could be made. Another SD model, constructed by the Department of Health in 2009 and later updated in 2011, supported policymaking and commissioning for KRT services for adults in England (Wild & Etim 2011). It projected the number of patients by dialysis modality and transplant over a ten-year period for use by Specialist Commissioning Groups at high level residence-based areas.

The age of the software these models were built in, password protected files, lack of licenses for commercial software within the NHS and lack of open access to adapting externally commissioned models, meant that Kidney Networks around the UK were mostly using excel-based forecasting models to plan future demands for services. HHD, pre-emptive transplant and conservative care needed to be added, as well as addressing other factors that may influence CKD’s progression to a stage requiring KRT, such as increased use of medications to slow the progression of CKD. A model was needed that would reflect the current patient pathways and give insight to relevant scenarios of future demand. The model needs to be scalable, with adaptable parameters, and available for use across the NHS.

2.2 Facilitated Hybrid Simulation

Hybrid simulation combines various methods, techniques, and/or paradigms for a more comprehensive understanding of complex socio-technical systems in real-world settings (Tolk et al. 2024; Brailsford et al. 2019). The development of hybrid simulation models requires the involvement of expertise from various stakeholders who are part of these complex systems. This means that modellers in the team must engage effectively with heterogeneous groups of external stakeholders while working with a collection of simulation methods and techniques efficiently. Like facilitated modelling, facilitated hybrid simulation includes the design of workshop sessions with interactive activities to engage stakeholder groups into the modelling process (Tako and Kotiadis 2015). It aims to achieve common modelling objectives between the modelling team and the stakeholders responsible for the systems under study via mutual understanding, group discussions, and consensus reaching activities (Eldabi et al. 2019). The PartiSim framework (Tako and Kotiadis 2015 and 2018) offers a structured approach for stakeholder engagement while also being flexible to involve other simulation techniques and paradigms.

Recent hybrid modelling and simulation studies applied to healthcare has mainly focused on emergency departments and acute care, long-term condition services and elderly care units, integrating simulation and modelling with policy development (Cassidy et al. 2019). The combination of simulation approaches (DES and SD) for healthcare has emerged since the 2010s (Kar et al. 2024). Existing literature guiding hybrid model development consists primarily of a toolkit for the design of the combination (Morgan et al 2017) and a framework for conceptual modelling development (Ngyuen et al 2024). There is however, little guidance on how to effectively engage stakeholders in the modelling process in hybrid modelling, apart from a study by Jones et al (2022) applied to the transport sector.

3 METHODS

3.1 Approach to Modelling Kidney Care

We develop a hybrid model that combines SD and DES that leverages the strengths of both approaches to offer the a holistic view of kidney care services . SD lends itself well to population-level disease modelling. It provides a high-level, aggregated view of the system, capturing feedback loops and long-term trends, such as the impact of interventions and health policy changes on patient populations. People in various stages of CKD are modelled as stocks, and their progression through these stages are represented by flows. DES is chosen due to its ability to model future prevalence of KRT based on patient demographics, clinical outcomes, and resource availability. It allows for detailed simulation of patient entities through healthcare processes over time. It can account for the duration between events of change in treatments and mortality. It can also represent resource-constrained processes and the prioritisation in queues such as transplant waiting lists. Additionally, DES can incorporate uncertainties in patient outcomes and treatment practices, providing scenario analysis and supporting decision-making in kidney care with a measure of variability in the results rather than a single output. A sequential design (Morgan et al. 2017) describes how the SD and DES models link conceptually (Figure 1). The SD model that tracks the progression of disease at population level, feeds the number of patients with CKD into the DES model, which in turn tracks the service capacity levels for KRT .



Figure 1: Conceptual representation of the hybrid SD-DES kidney care model of a sequential design

This hybrid SD-DES model can simulate both individual patient pathways and system-wide dynamics, enabling a comprehensive understanding of the future demands for KRT services, while considering the impacts of both upstream and downstream interventions. By assessing the long-term impacts, policymakers and healthcare providers can determine resource allocation and plan for changes in demand across treatment modalities. One challenge of developing such a hybrid model lies in how to facilitate a diverse stakeholder group to participate in defining and developing a model that operates across differing time scales and levels of granularity.

To tackle this challenge, this study combines three key elements to support the model development: participative modelling workshops, evidence mapping and patient experience pathways.

The evidence mapping provided an overview of the evidence base to inform the modelling team of the kidney care, covering aetiology, diagnosis, treatment, prognosis, prevention, as well as past modelling approaches. The patient experience pathway explores the way that patients understand and experience their pathway, which is broader than their traditional engagement with individual services, extending further the work of Tako et al (2019). The patient experience pathway will be used to validate the modelling work, improve our understanding of early intervention, accessibility and inequity issues, and identify changes to models of care that might be the most suitable.

We develop a customised participative modelling approach that combine elements from Partisim (Tako and Kotiadis 2015), Simtegr8 (Tako et al 2019) and Scriptapedia (<https://en.wikibooks.org/wiki/Scriptapedia>, accessed 17th Nov 2024) to inform the approach and activities included in the facilitated workshops with a diverse group of stakeholders.. Based upon existing models in the literature and pre-understanding of the problem from the initial evidence mapping, the team developed preliminary models prior to the facilitated workshops. These models served as prompts to facilitate the discussion and analytical thinking at the workshops, where the modelling team gathered feedback from the stakeholders to further develop these models. Refined models were then presented back to the stakeholders and validated with the stakeholder group. The following section presents an overview of the facilitation process.

3.2 The Facilitation process

Five workshops are planned in total, of which three have already taken place. A summary of the three workshops held so far is provided in Table 1.

Table 1: Summary of workshops 1-3, detailing the participants, workshop format and outcomes

Items	Workshop 1	Workshop 2	Workshop 3
Number of participant	10	11	11
Duration	3 hours	6 hours	3 hours
Location	In person	In person	Online
Structure	1. Introduction and setting the scene (30') 2. Objective elicitation (30') 3. Developing problem definition (40') 4. Demand and capacity problems in current kidney services (60') 5. Summary and close (5')	1. Introduction and recap (25') 2. Causal loop diagram explanation and exercise (15') 3. SD modelling exercise (95') 4. DES modelling exercise (70') 5. Model objectives 'How to measure success' (60') 6. Summary and close (5')	1. Introduction and recap (20') 2. SD model part walkthrough (70') 3. DES model walkthrough (50') 4. Group reflections and discussion (30')
Workshop Aims	- Identify and formulate the problem; - Develop a common understanding of the problem situation with the model build group; - Agree on overall study objectives.	- Further developed two detailed diagrams of: a) KRT services and b) kidney disease progression in the population; - Define the model objectives.	- Validate/Review/Adjust the assumptions adopted by the conceptual models with stakeholders; - Refine data requirements and identify data sources.
Preliminary model	A simple DES model based on previous studies	Two high level models DES and SD models were presented to help conceptualisation.	Two more detailed DES and SD models developed by the team were presented to gather feedback and for verification.
Workshop Outcomes	A problem statement under the CATWOE framework is formulated and important factors to consider for demand and capacity are discussed.	Revised causal loop diagrams and simulation models are created, pathways of care for different categories of kidney patients discussed.	Revision/Confirmation of DES model assumptions; References of data sources; Testing scenarios to experiment identified; Stakeholders gain a clear understanding of model outcomes.

3.2.1 Preliminary problem formulation workshop

The Strategy Unit and the Midlands Kidney Network met virtually for a preliminary problem formulation workshop in May 2023. The aims of this workshop were to: 1) Consider the purpose of the modelling work and to create engagement amongst the stakeholder group for the next steps.

The discussions during this workshop helped inform the modelling team to gain insight into differing perspectives on how kidney care services may change. Participants were guided through facilitated discussion in 3 steps using questions to guide their thinking through the past, current and future of kidney care services. Notes and comments were added virtually to an online note board. There was a brief discussion of potential methods and questions that the model could potentially explore. There was a significant pause whilst waiting for the funding for the project to be secured.

3.2.2 Workshop 1: Defining the problem

Workshop 1 focused on problem definition, which consisted of a 3-hour in-person facilitated session. Various activities were designed to help the participants identify current problems faced by kidney care services and consider changes needed. In the end, a problem statement using the CATWOE framework was formulated and important factors to consider for demand and capacity were discussed. The participants identified issues such as demand/capacity mismatch, inequality in outcomes compared to ethnicity, as well as additional bottlenecks in the KRT pathway. Prevention and slowing disease progression were identified amongst the main interventions to improve future kidney care service provision. Members of the evidence team were included in both in-person workshops (Workshops 1 & 2) to understand the context of the evidence required so they could support the parameterisation and assumptions made in the modelling.

3.2.3 Workshop 2: Defining the model

Workshop 2 took place two weeks after Workshop 1 as a whole-day in-person event that focused on scoping the conceptual model of the CKD progression and kidney care services using causal loop diagrams (CLDs) for the SD model and process flow diagrams (PFD) for the DES model. The modelling team prepared one preliminary CLD depicting the different stages of kidney disease progression in the patient population and one preliminary PFD depicting the whole kidney care system for kidney replacement therapy services and asked participants for comments and additions.

3.2.4 Workshop 3 Model Refinement

Workshop 3 took place online, 2.5 months after Workshop 2. It focused on model validation, testing and scenario identification, lasting approximately 3 hours. Between Workshop 2 and 3, the modelling team worked on refining the SD and DES models based on the comments received in Workshop 2. In this workshop, the participants and the modelling team discussed the model assumptions, data requirements, data sources, model outcomes and ‘what-if’ scenarios. The modelling team and stakeholders also agreed on the next action plans. Two additional SD and DES model validation workshops were planned, followed by a final model implementation workshop.

4 THE KIDNEY CARE SD AND DES MODELS

The two preliminary DES and SD models developed iteratively with the input of the stakeholder group in the first three workshops are next described.

4.1 System dynamics model of kidney disease progression

Due to difficulties in recognising and diagnosing early-stage CKD (stages 1 and 2), the disease progression SD model focused on the more advanced stages of CKD, from stage 3 through to stage 5 and then to those needing KRT. Figure 2 shows a simplified structure of the SD model, built using Stella Architect (isee systems, <https://www.iseesystems.com/>, accessed 28 January 2025). The four stocks on the left-hand side represent people with CKD at stages 3-5 and are split between diagnosed and undiagnosed. The flows indicate progression through the various stages and diagnosis states. The ‘KRT’ stock represents people who are either on dialysis or who have received a kidney transplant. Auxiliary variables affect the flow rates in and out of the model, and between the stocks. Interventions can also be incorporated into the model. For instance, a ‘primary prevention’ intervention would influence the ‘CKD incidence’, whereas a disease management intervention would slow progression between CKD stages and decrease the mortality at each stage.

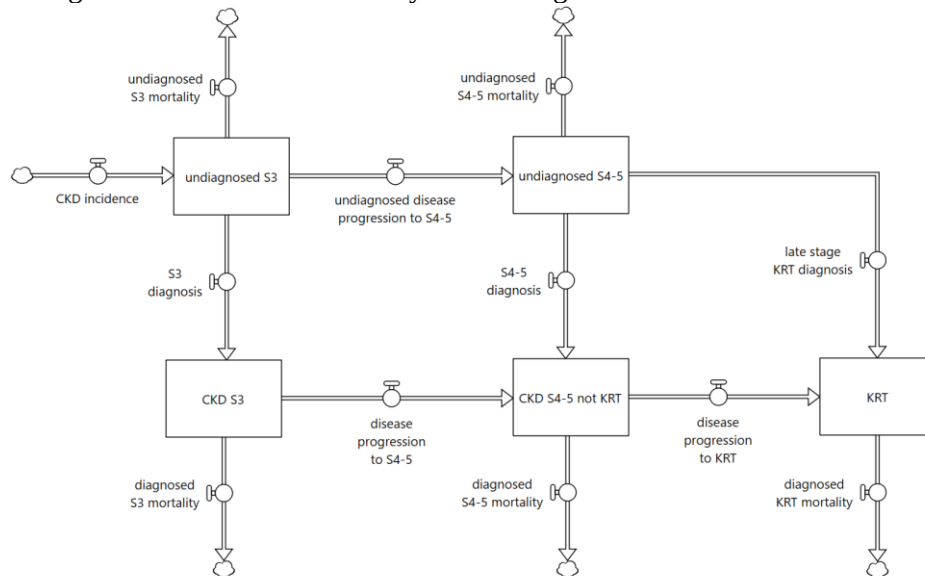


Figure 2: Overall structure of the SD model: key stocks and flows representing the various stages of chronic kidney disease

The model is parameterised using data from many sources, identified together with stakeholders in the participative workshops. Data sources include CVD Prevent (<https://www.cvdprevent.nhs.uk/>), the UK Renal Registry (2024), and findings from the Inside CKD microsimulation (Chertow et al. 2024). The flow rates were approximated by calibrating the model to fit the historical reported prevalence, using a Powell Optimization algorithm. The simulation runs for a time span of 20 years, from 2016 to 2035. The baseline model assumes the status quo that is no intervention is implemented.

4.2 Discrete-event simulation model of kidney replacement therapies services

The DES models the incidence of kidney transplant and the prevalence of different modes of dialysis and functioning kidney grafts to allow for service planning over a 20-year period. A high-level representation of the DES model is illustrated in Figure 3. The model integrates the prevalence of patients by dialysis modality, the number of live and deceased donor transplants and the prevalence of functioning grafts for each simulated year. The model extends the prevalence of dialysis and kidney transplant model developed by (Roderick et al. 2004) to allow the investigation of additional interventions such as increasing home therapies through a combination of HHD and PD, diverting additional patients to conservative kidney care management, increasing live kidney donations, improvements to the speed of transplant work up, decreasing late presentation and increasing pre-emptive transplants (before dialysis is required).

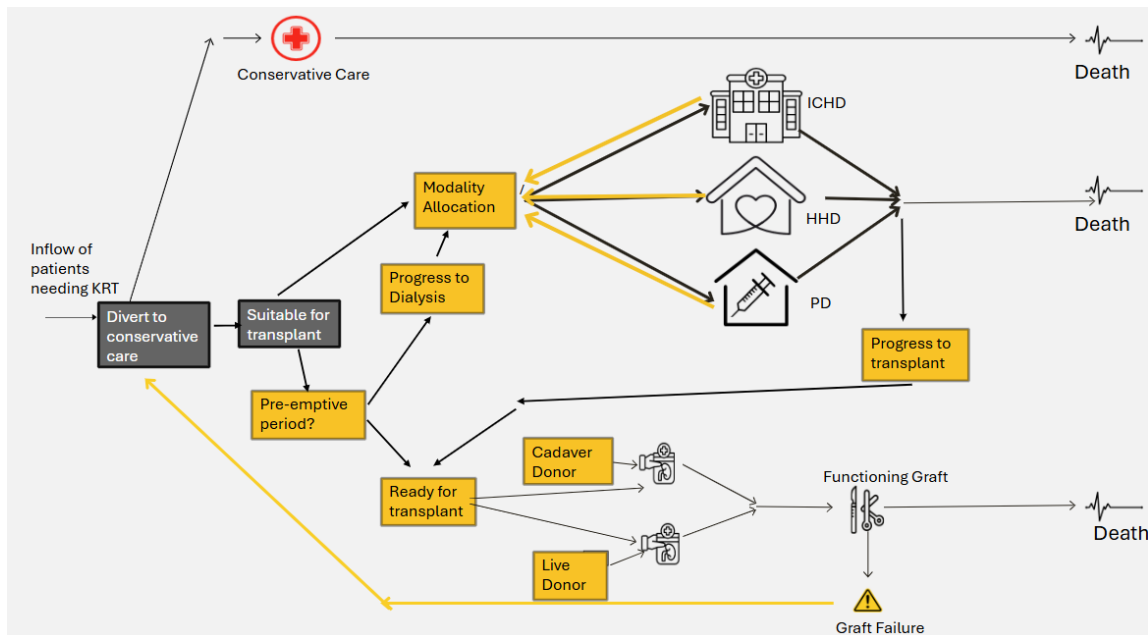


Figure 3: A high-level representation of the DES model

The DES model commences at the point when a patient requires KRT. It allows a proportion of patients to be diverted to conservative kidney management. Those who are not diverted to conservative care and unsuitable for transplant go on to receive dialysis. Those suitable for transplant can either a) receive dialysis whilst awaiting transplant, b) wait for transplant without needing dialysis initially and then require dialysis before being transplanted or c) pre-emptively receive kidney transplant without requiring dialysis. When functioning grafts fail, the patients may either die or re-enter the KRT pathway in the model. During the receipt of dialysis or a functioning graft and in conservative kidney management, it is possible for patients to leave the model through mortality. The DES model was constructed in Simul8 Professional (build no. 31.0.4730).

The model is parameterised using an example kidney care centre and drawing on data from published reports from UK Renal Registry (2024) and NHS Blood and Transplant (2024), historic

parameters from the West Midlands version of the previous model, unpublished analysis of UK Renal registry data, and estimates from discussions with subject matter experts following the facilitated workshops.

5 CONCLUSIONS AND FUTURE WORK

This paper presents a simulation modelling study carried out to support capacity planning of care services for Chronic Kidney disease (CKD) in the UK. The aim of the study was to develop a generic model that can be customised with data to be used by local kidney care services across the UK. The study adopts a hybrid modelling approach combining SD and DES models. It offers an effective and detailed representation of the whole kidney care system including both kidney disease progression that triggers demand for kidney care (SD part of the model) and capacity requirements for KRT from a service level perspective (DES part of the model).

The study is the first to offer a hybrid simulation model that leverages the strengths of both approaches to analyse the future demand for KRT. The SD-DES model has potential to simulate both individual patient pathways and system-wide dynamics. It can offer a comprehensive representation of the future demands for KRT services, while considering the impacts of both upstream and downstream interventions at patient population level and at care service delivery level. Developing such a model that operates across different time units and levels of granularity poses challenges in facilitating and engaging a diverse stakeholder group.

The study combined a wide range of stakeholders including clinicians, commissioners, service managers, nurses and patients to draw diverse perspectives into the models and the scenarios tested. Four workshops have so far taken place, with three more planned. A preliminary workshop established appetite for the project. Workshop 1 considered the wider kidney care system and issues affecting efficient provision of services. Workshop 2 scoped out the conceptual model. It is noted that the simulation models were developed iteratively by the modelling team from pre-workshop 1, while more details were added as information was elicited at the two workshops. The format of workshops varied, with Workshop 1 and 2 in person while Workshop 3 online to fit into stakeholders' time and availability. The workshop activities were varied to ensure effective involvement of the stakeholder group using individual and group activities, including objective cards, whiteboard, post-it, flipchart, pre-printed conceptual models. These interactive activities guided the communication during the workshops and enhanced stakeholder engagement. Questionnaires distributed after workshops 1 and 2 measured the participants' perception about the communication, commitment, consensus and usefulness of the model and the workshops. Participants gave very positive feedback across all categories of questions. This paper illustrates a novel example of adopting a facilitated approach for co-creating hybrid simulation models with a group of stakeholders. To our knowledge so far this is the only hybrid SD-DES model developed adopting a fully facilitated mode. The facilitation process adopted differs to that of existing facilitated studies in the literature to suit the data and conceptual model elicitation requirements of the two modelling approaches we use.

It is acknowledged that the study faced several limitations, including issues with data availability. The model currently does not include capacity data for both staff and dialysis slots. The UK Kidney Network is currently undertaking a capacity audit which we hope will inform conversion of demand to capacity requirements. The models presented are still at a preliminary stage and will need to be linked to feed data into each other. Whilst commercial software has been used to aid stakeholder interaction with the development of the models and their validation, the intent is for these preliminary models to be developed into a free and open-source tool for wider use within the NHS. Plans to redevelop and combine the models in open-source python modelling tool (Palmer and Tian 2021) are in place to enable further validation, deployment and embedding into service planning. The NHS aim to develop a web interface using Shiny (<https://shiny.posit.co/>, accessed 23rd Jan 2025) to enable wider sharing of the model by other Kidney Networks across the UK.

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