Health Systems (2017)

www.palgrave.com/journals

Open

REVIEW ARTICLE

A systematic literature review of operational research methods for modelling patient flow and outcomes within community healthcare and other settings

Ryan Palmer[1], Naomi J. Fulop[2] and Martin Utley[1]

[1]Clinical Operational Research Unit, Department of Mathematics, University College London, 4 Taviton Street, London WC1H 0BT, UK;
[2]Department of Applied Health Research, University College London, London, UK

Correspondence: Ryan Palmer, Clinical Operational Research Unit, Department of Mathematics, University College London, 4 Taviton Street, London WC1H 0BT, UK

Abstract
An ambition of healthcare policy has been to move more acute services into community settings. This systematic literature review presents analysis of published operational research methods for modelling patient flow within community healthcare, and for modelling the combination of patient flow and outcomes in all settings. Assessed for inclusion at three levels – with the references from included papers also assessed – 25 "Patient flow within community care", 23 "Patient flow and outcomes" papers and 5 papers within the intersection are included for review. Comparisons are made between each paper's setting, definition of states, factors considered to influence flow, output measures and implementation of results. Common complexities and characteristics of community service models are discussed with directions for future work suggested. We found that in developing patient flow models for community services that use outcomes, transplant waiting list may have transferable benefits.
Health Systems (2017). doi:10.1057/s41306-017-0024-9

Keywords: literature review; community healthcare; patient flow; outcomes; operational research

The online version of this article is available Open Access

Introduction

In recent decades, an ambition of healthcare policy has been to deliver more care in the community by moving acute services closer to patient homes (Munton *et al*, 2011; NHS England, 2014). This is often motivated by assumed benefits such as reduced healthcare costs, improved access to services, improved quality of care, a greater ability to cope with an increasing number of patients, and improved operational performance in relation to patient health and time (Munton *et al*, 2011).

A scoping review analysed the evidence regarding the impact that shifting services may have on the quality and efficiency of care (Sibbald *et al*, 2007). It found that under certain conditions moving services into the community may help to increase patient access and reduce waiting times. Across multiple types of care, however (minor surgery, care of chronic disease, outpatient services and GP access to diagnostic tests), the quality of care and health outcomes may be compromised if a patient requires competencies – such as minor surgery – that are considered beyond those

Received: 8 June 2016
Revised: 16 December 2016
Accepted: 6 January 2017

of the average primary care clinician. On the evidence for the effect on the monetary cost of services, Sibbald *et al* (2007) stated that it was generally expected that community care would be cheaper when offset against acute savings; however, increases in the overall volume of care (Hensher, 1997) and reductions in economies of scale (Powell, 2002; Whitten *et al*, 2002) may lead to an increase in overall cost in certain instances.

Considering the questions that remain over the impact of shifting services from acute to community sector, it is important to understand how community services may be best delivered. This is where applying operational research (OR) methods to community care services can contribute. For instance, services may be modelled to evaluate how goals, such as better patient access and improved outcomes, may be achieved considering constraints and objectives, such as fixed capacity or reducing operational costs. An example of one such method is patient flow modelling, the focus of this review.

Modelling patient flow

In a model of flow, the relevant system is viewed as comprising a set of distinct compartments or states, through which continuous matter or discrete entities move. Within healthcare applications, the entities of interest are commonly patients (although some applications may consider blood samples or forms of information). Côté (2000) identified two viewpoints from which patient flow has been understood, an operational perspective and, less commonly, a clinical perspective. From an operational perspective, the states that patients enter, leave and move between are defined by clinical and administrative activities and interactions with the care system, such as consulting a physician or being on the waiting list for surgery. Such states may be each associated with a specific care setting or some other form of resource but this need not be the case. In the clinical perspective of patient flow, the states that patients enter, leave and move between are defined by some aspect of the patient's health, for instance by whether the patient has symptomatic heart disease, or the clinical stage of a patient's tumour. A more generic view is that the states within a flow model can represent any amalgam of activity, location, patient health and changeable demographics, say, patient age (Utley *et al*, 2009). A key characteristic is that the set of states and the set of transitions between states comprise a complete description of the system as modelled.

Within the modelling process, characteristics of the patient population and of the states of the system are incorporated to evaluate how such factors influence flow. Examples of the former include patient demographics or healthcare requirements, whilst for the latter, capacity constraints relating to staffing, resources, time and budgets may be considered. The characteristics used depend upon the modelled system, modelling technique and questions being addressed. Considering these, the performance of a system may be evaluated through the use of output measures such as resource utilisation (Cochran & Roche, 2009), average physician overtime (Cayirli *et al*, 2006) and patient waiting times (Zhang *et al*, 2009).The output measures calculated within an application depends upon the modelled problem, modelling technique and the factors that are consider to influence flow.

Within acute care settings patient flow modelling has been applied to various scenarios – see Bhattacharjee & Ray (2014). There are also several publications for community care settings; however, no published literature review exists. This systematic literature review was undertaken to gather and analyse two types of patient flow modelling literature relevant for community services. The first were publications that present models of operational patient flow within a community healthcare context, denoted as "Patient flow within community care". The second were publications that present combinations of patient outcomes and patient flow modelling in any setting, denoted as "Patient flow and outcomes". Incorporating patient outcomes within the patient flow modelling process is increasingly pertinent within community healthcare. Patient outcomes are used not only to track, monitor and evaluate patient health throughout a care pathway, but also assess the quality of care and inform improvement. The justification for increasing the provision of community care includes improved patient outcomes and satisfaction, thus in combining outcomes and patient flow modelling new and helpful metrics may be developed to evaluate this assertion. Furthermore, such methods help to inform the organisation of healthcare services according to operational capability and the clinical impact on the patient population, unifying two main concerns of providers and patients with a single modelling framework. No specific setting was sought in the "Patient flow and outcomes" to find potentially transferable knowledge and methods for community settings.

To the best of our knowledge, this is the first literature review focussing on OR methods for modelling patient flow applied to community healthcare services and the first to review methods for modelling patient flow and outcomes in combination. This review has been undertaken as part of a project in which OR methods will be developed that combine patient flow modelling and patient outcomes for community care services. The aim of this review was thus twofold. Firstly, to explore different applications of OR methods to community services. Secondly, to understand how patient outcomes have been previously incorporated within flow models. In the discussion section of this paper, we suggest directions for the future of patient flow modelling applied to community care.

Method of review

We conducted a configurative systematic literature review (Gough *et al*, 2012), an approach intended to gather and analyse a heterogeneous literature with the aim of identifying patterns and developing new concepts. Two searches were performed to find peer-reviewed operational research (OR) publications, relating to "Patient flow within community care" and "Patient flow and outcomes" as previously detailed. We considered all papers published in English before November 2016 with no lower bound publication date, and searched the electronic databases Scopus, PubMed and Web of Science. Using a combination of the search terms listed in Table 1, to find papers related to "Patient flow within community care" we sought records with at least one operational research method term in the article title, journal title or keywords AND at least one patient flow term in the article title, journal title, keywords or abstract AND at least one community health setting term in the article title, journal title, keywords or abstract. Likewise, to find papers related to "Patient flow and outcomes" we sought records with at least operational research method term in the article title, journal title or keywords AND at least one patient flow term in the article title, journal title, keywords or abstract AND at least one outcome term in the article title, journal title, keywords or abstract.

Initial sets of search terms relating to community healthcare settings and OR methods were informed by Hulshof *et al* (2012). Synonyms were added to these lists prior to the preliminary searches for papers. For patient flow terms and outcome terms, we formed initial lists that we considered relevant. The first batch of papers found using these lists was examined for further applicable search terms. The initial search terms are highlighted in bold in Table 1.

Papers obtained from the final searches were assessed for inclusion for full review at three levels. If a paper was not a literature review it was required to meet all the inclusion and none of the exclusion criteria outlined in

Table 1 Final terms for literature searches

OR method terms	*Patient flow terms*	*Setting terms*	*Outcome terms*
Computer simulation	Access time	Community based	Outcome
Discrete event simulation	Bed occupancy	Community clinic	Patient class
Heuristics	Capacity allocation	Community facility	Patient type
Markov chain	Capacity management	Community level	Quality of life
Markov decision	Capacity planning	Diagnostic facilities	Readmission
Markov model	Care management	Health care center	Referral
Mathematical model	Patient flow	Health care centre	*Disease progression*
Mathematical programming	Patient pathway	Health care clinic	*Health status*
Metaheuristics	Patient process	Health care practice	
Operational management	Patient route	Health care service	
Operational research	Patient throughput	Health center	
Operations management	Process flow	Health centre	
Operations research	Wait time	Health clinic	
Optimisation	Waiting list	Health facility	
Optimization	Waiting time	Healthcare center	
Queueing	*Care access*	Healthcare centre	
Queuing	*Demand management*	Healthcare clinic	
Simulation model	*Flow of patients*	Healthcare facility	
System dynamics	*Patients' flow*	Healthcare practice	
Integer programming	*Flow of care*	Healthcare service	
Linear programming		Home care	
Modelling patient		Home health care	
Network analysis		Long term care	
Stochastic analysis		Mental health	
Stochastic modelling		Primary care	
Stochastic processes		*Care facility*	
Visual simulation		*Community care*	
		Community health	
		Community healthcare	
		Homecare	
		Medical center	
		Medical centre	
		Multi facility	
		Multiservice	
		Residential care	
		Walk in	

Table 2 Inclusion and exclusion criteria for assessing papers presenting models of patient flow

Assessment level	*Criteria*	*Patient flow within community care*	*Patient flow and outcomes*
Title and journal	Inclusion	At least one operational research method term in the article title, journal title or keywords AND At least one patient flow term in the article title, journal title, keywords or abstract AND At least one community health setting term in the article title, journal title, keywords or abstract	At least one operational research method term in the article title, journal title or keywords AND At least one term patient flow term in the article title, journal title, keywords or abstract AND At least one outcome term in the article title, journal title, keywords or abstract
		English language; published before November 2016 in peer-reviewed journals	
	Exclusion	Title or journal of publication had no relevance to OR, healthcare or patient flow	
Abstract	Inclusion	Abstract suggested that the paper focussed on operational processes of healthcare and that OR methods were used to model patient flow	
	Exclusion	Papers based within management settings other than operational management The delivery of healthcare was not evaluated Only different scheduling policies were evaluated	
		Abstract indicated that the paper was not based in community care	Abstract indicated that the paper did not use patient outcomes
Full text	Inclusion	Abstract level inclusion criteria met in the full text A model was presented using mathematical concepts and language The model was well specified and reproducible Quantitative analysis of a healthcare system was conducted within the paper	
	Exclusion	Criteria for exclusion at abstract level met in the full text A model was viewed only in terms of its inputs and outputs without knowledge of its internal workings A model was formulated as a composition of concepts that could not be used for analysis A model was not rooted in analysis	

Table 2. For each included paper, references were assessed using the same inclusion and exclusion process to find any papers that may have been missed in the searches.

Literature reviews were included at each level if they were concerned with OR methods for evaluating patient flow; focussed on operational processes of healthcare and no equivalent systematic review was included. Within the "Patient flow within community care" literature, review pieces were included if they focussed on community settings; whilst within the "Patient flow and outcome" literature, review pieces were included if they focussed on uses of patient outcomes in modelling processes.

Data tables were constructed to present key characteristics of the literature and shape our analysis. Informed by the initial readings, papers were grouped into five categories based on analytical method with five key characteristics of each model extracted and tabulated for comparison, given in Tables 4, 5 and 6.

Results of literature searches

The results of the final searches for and selection of papers are shown in an adapted PRISMA flow chart (Moher *et al*, 2009), Figure 1. Reasons for the exclusion of texts at full text assessment are shown in Table 3.

Overall 25 "Patient flow within community" papers, 23 "Patient flow and outcomes" papers and 5 papers in the intersection entered the full review. An analysis of this literature is now presented with in the intersection of the two searches included in the "Patient flow within community care" section.

Analysis

Papers found within the "Patient flow within community care" search

Markovian models A Markovian model views flow within a system as a random process within which the future movement of an entity is dependent only upon its present state and is independent of time spent in that state or the pathway it previously travelled. Whilst systems of healthcare are not truly Markovian, in using these methods, a steady-state analysis of a system may be formulated from which meaningful long-run averages of system metrics can be calculated.

The settings of these publications, presented in Tables 4 and 5, include residential mental healthcare (Koizumi *et al*, 2005), post-hospital care pathways (Kucukyazici *et al*, 2011), community services and hospital care (Song *et al*, 2012) and community-based services for elderly patients with diabetes (Chao *et al*, 2014).

Within these models, states were defined as different services or stages of care. Kucukyazici *et al* (2011) and Chao *et al* (2014) also defined states of post-care outcomes. In the former these included patient mortality,

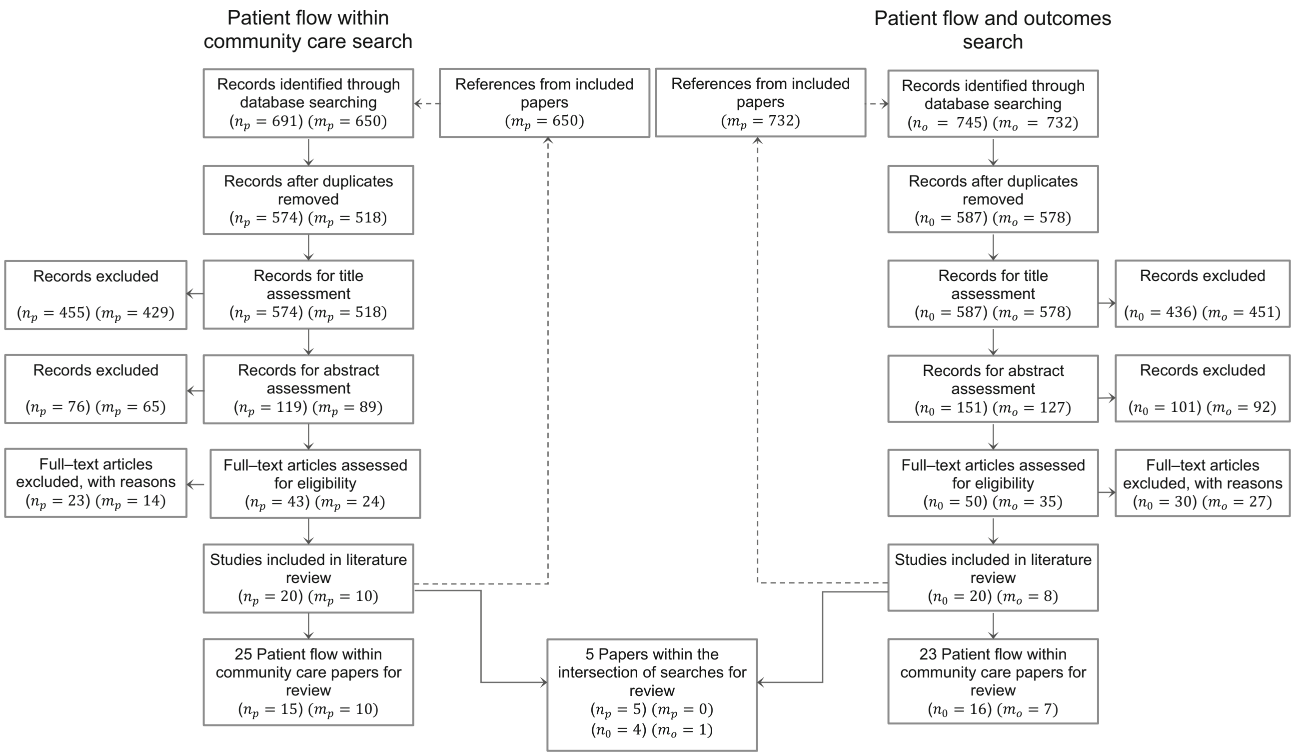

Figure 1 Flow chart of literature search results – 53 papers were eligible for review.

Table 3 Reasons for exclusion at full text assessment

Number of papers excluded at full text assessment	*Reason for exclusion*				
	No OR/patient flow modelling	*Non-community settings*	*Model not reproducible/ specified//quantitative*	*Analysis of different scheduling policies*	*No patient outcomes*
23 "Patient flow within community care" literature	5	8	7	3	N/A
14 "Patient flow within community care" references	2	8	3	1	N/A
30 "Patient flow and outcomes" literature	8	N/A	2	7	13
27 "Patient flow and outcomes" references	4	N/A	–	1	22

admission to long-term care and re-hospitalisation, whilst the latter defined states of subsequent health progression.

Two main factors were considered to influence flow within these models: the effect of congestive blocking caused by limited waiting space (Koizumi *et al*, 2005; Song *et al*, 2012) and the diversity of patients: demographics (Kucukyazici *et al*, 2011) and severity of disease (Chao *et al*, 2014). In considering blocking, flow was influenced by the available capacity and average occupancy of each service.

The output measures were queue lengths and wait times for each state – with and without congestive blocking (Koizumi *et al*, 2005; Song *et al*, 2012) and the probability that patients would be in a given post-care outcome state (Kucukyazici *et al*, 2011; Chao *et al*, 2014). An analysis of different scenarios was undertaken in both latter papers to identify how alternative treatments may help improve post-care outcomes.

None of the papers explicitly reported implementation of their results. We consider implementation to include any action to share or use the results of the work within the modelled setting.

Non-Markovian steady-state models An optimisation approach for resource allocation by Bretthauer & Côté (1998) defined states as services within specified pathways. The aim was to minimise overall costs whilst maintaining a certain level of care as measured by metrics such as desired waiting. Within the model, flow was influenced by capacity constraints, such as number of beds.

Table 4 Papers included from "Patient flow within community care" search only

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Markovian models						
Modeling patient flows using a queuing network with blocking	Koizumi *et al* (2005)	Community care – mental health –Physical queues	Multiple residential services	Service capacity Traffic intensity per service Congestive blocking	Queue lengths and wait times – with and without blocking	Not explicitly stated
A block queueing network model for control patients flow congestion in urban healthcare system	Song *et al* (2012)	Community and hospital pathways –Physical queues	Community services Hospital registration General hospitals	Service capacity Traffic intensity per service Congestive blocking Batch arrival process	Queue lengths and wait times – with and without blocking	Not explicitly stated
Non-Markovian steady state analysis						
A model for planning resource requirements in health care organizations	Bretthauer & Côté (1998)	General approach, examples: blood bank, health maintenance organisation –Physical queues	Different services Stages of care	Resource constraints e.g. Number of clinicians Performance constraints e.g. Wait time Multiple time period extension	Optimised total capacity costs	Not explicitly stated
System dynamics analysis						
A patient flow perspective of U.K. health services: exploring the case for new "immediate care" initiatives	Wolstenholme (1999)	UK health service –Physical and non–physical queues	Primary care Secondary care Community care NHS continuing care	Volume of patients arriving Service capacity	Queue lengths Waiting times Bed occupation Scenario analysis Long run use of services	Some insights shared with NHS staff
Simulation analysis of the consequences of shifting the balance of health care: A system dynamics approach	Taylor *et al* (2005)	Community and acute care Non-physical queues	Cardiac services in community	Wait time Size of waiting list Feedback mechanism Clinical guidelines Service capacity	Average wait times Cumulative patient referrals and activity Overall cost of care Scenario analysis	Collaboration noted
Analytical methods featuring time dependence						
A continuous time Markov model for the length of stay of elderly people in institutional long-term care	Xie *et al* (2005)	Long-term care –Physical queues	Residential home care Nursing home care –Long stay –Short stay	Maximum likelihood estimation (MLE) of model parameters	Sojourn time Estimation of LOS Patterns of care usage	Not explicitly stated

Table 4 (Continued)

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
A model-based approach to the analysis of patterns of length of stay in institutional long-term care	Xie *et al* (2006)	Long-term care –Physical queues	Residential home care Nursing home care –Long stay –Short stay	MLE of model parameters Left truncated data Right censored data Patient characteristics: –Previous care –Gender	Sojourn time Estimation of LOS Patterns of care usage	Not explicitly stated
Analytical methods for calculating the distribution of the occupancy of each state within a multi-state flow system	Utley *et al* (2009)	Community mental health care –Uncapacitated demand	General states Illustrated with states as different stages of care	Time spent in state	Time dependent distribution for occupancy of states	Suggestions made to stake holders
A deterministic model of home and community care client counts in British Columbia	Hare *et al* (2009)	Long-term care –Uncapacitated demand	Different aspects of LTC: –Home care –Accommodation Care environment –Publicly funded/ non-publicly funded	Time varying population characteristics: –Patient age –Wealth –Health status Initial conditions	Future demand for each aspect of LTC	Model used for planning future care
A mathematical modelling approach for systems where the servers are almost always busy	Pagel *et al* (2012)	Community mental health care –Non-physical queues	Different services	Capacity constraints e.g. Appointment slots Servers must always be busy (no steady state)	Optimal appointment allocation subject to wait time and capacity constraints	Formulation of a tool
Appointment capacity planning in specialty clinics: a queueing approach	Izady (2015)	Specialty clinics –Physical queues	Waiting In service	Abandonment –Fixed –Backlog dependent Patients able to re-join queue Capacity Appointment type	Patient wait time Queue length Size of appointment queues No-show probability Referral variance Panel size	Not explicitly stated

Table 4 *(Continued)*

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Simulation Analysis						
Improving outpatient clinic efficiency using computer simulation	Clague *et al* (1997)	Outpatient-genito urinary medical clinic –Physical queues	Stages of care	Patient groups: –Clinical staff required –New or returning Mixed arrivals No shows Staffing constraints	Patient wait time Doctor wait time Clinic overtime Scenario analysis	Application of method in response to a feedback survey
Evaluating the design of a family practice healthcare clinic using discrete-event simulation	Swisher & Jacobson (2002)	Family Practice Healthcare Clinic –Physical queues	Stages of care Locations in the clinic	Patient groups: –Health Mixed arrivals No shows Staffing constraints	Patient wait time Staffing costs Revenue Clinician overtime Scenario analysis Staff utilisation Facility utilisation	Not explicitly stated
Improving patient flow at an outpatient clinic: Study of sources of variability and improvement factors	Chand *et al* (2009)	Outpatient clinic –Physical queues	Stages of care Stages of patient information flow	Variability in task times Patient characteristics: –New or returning –Administrative characteristics	Patient wait time Physician overtime: –AM and PM Scenario analysis	Some suggested changes have been implemented
Reducing patient wait times and improving resource utilization at British Columbia Cancer Agency's ambulatory care unit through simulation	Santibáñez *et al* (2009)	Community care-ambulatory care unit –Physical queues	Stages of care process	Shared resources Appointment type Capacity constraints Scheduling policy	Scenario analysis Patient wait time Appointment duration Resource utilisation Time in system Clinician utilisation	Suggestions made to senior management
Facilitating stroke care planning through simulation modelling	Bayer *et al* (2010)	Stroke services –Physical and non-physical queues	Stages of a stoke pathway –Acute –Community	Patient groups: –Health related Probabilistic: –Death rate –Length of stay Capacity constraints	Scenario analysis Predicted bed days –Acute –Care home Cost of providing resource	Not explicitly stated
Using discrete event simulation to compare the performance of family health unit and primary health care centre organizational models in Portugal	Fialho *et al* (2011)	Primary healthcare –Non-physical queues	Stages of clinic care	Administrative characteristics Consultation type Opening hours Duration of appointment Routes of care	Days to arrange a GP consultation Annual number of different consultations Waiting time Financial costs	Not explicitly stated

Table 4 *(Continued)*

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Modeling the demand for long-term care services under uncertain information	Cardoso *et al* (2012)	Long-term care –Uncapacitated demand	Different aspects of LTC: –Home based –Ambulatory –Institutional	Patient groups: –Demographics –Chronic disease –Level of dependency Mortality rates Capacity	Scenario analysis Future demand Resources required to meet demand for each aspect of LTC Cost	Not explicitly stated
A simulation Optimization Approach to Long-Term Care Capacity Planning	Zhang *et al* (2012)	Long-term care –Uncapacitated demand	Waiting In service	Patient characteristics: –Age and gender –Arrival rate –LOS Initial conditions	Scenario analysis Optimised capacity relating to waiting time targets Future demand/capacity	Collaboration, training and feedback highlighted
Applying discrete event simulation (DES) in healthcare: the case for outpatient facility capacity planning	Ponis *et al* (2013)	Outpatient clinics –Non-physical queues	Different services	Patient characteristics: –Administrative –Medical Budget constraints Capacity constraints Appointment types Abandonment Distance from clinic	Resource utilisation Cost of care Optimised service provision	Not explicitly stated
Developing an adaptive policy for long-term care capacity planning	Zhang and Puterman (2013)	Long-term care –Uncapacitated demand	Waiting In service	Patient characteristics: –Age and gender –Arrival rate –LOS Initial conditions Achievement of wait time targets in previous year	Scenario analysis Adaptive policy for capacity planning Optimised capacity relating to waiting time targets Future demand/capacity	Not explicitly stated

Table 4 (Continued)

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Simulation analysis on patient visit efficiency of a typical VA primary care clinic with complex characteristics	Shi *et al* (2014)	Primary healthcare clinic –Physical queues	Stages of care	Patient groups: –Arrival type –Care requirements No shows Number of double booked appointments	Service utilisation Wait time Factor study	Suggestions made to management
Patient flow improvement for an ophthalmic specialist outpatient clinic with aid of discrete event simulation and design of experiment	Pan *et al* (2015)	Specialist outpatient clinic –Physical queues	Stages of care and information flow Waiting	Patient characteristics: –Services required –Punctuality/no show Layout of clinic Resource capacity: –Staffing levels –Shared resource Inter-relation of patient flow and information flow Batch arrivals in information flow	Scenario analysis Turnaround time Waiting time Allocation of appointment slots	Implementation of results
A simulation model for capacity planning in community care	Patrick *et al* (2015)	Acute care Long-term care -Physical queues	Different services	Patient groups: –Care requirements –Priority –Preference Capacity Reneging	Scenario analysis Necessary capacity to meet target: –Wait time/list size –Percentage of patients who reach their preferred facility	Not explicitly stated
A simulation optimisation on the hierarchical health care delivery system patient flow based on multi-fidelity models	Qiu *et al* (2016)	Community care General hospitals –Physical queues	Community services General hospitals Stages of care	Patient groups: –Care requirements Profit Priority Inter-hospital flow	Queueing network: Optimised resources to achieve maximum profit Simulation: Evaluation of feasible solutions regarding: –Profit –Use of services –Cured patients	Not explicitly stated

Table 5 **Papers included from "Patient flow within community care" search and "Patient flow and outcomes" search**

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Markovian models						
An analytical framework for designing community-based care for chronic diseases	Kucukyazici *et al* (2011)	Community care-post acute services –Non-physical queues	Different services Post care outcomes	Demographics of inter service flow	Scenario analysis Likely post care outcomes for common pathways	Not explicitly stated
The long-term effect of community-based health management on the elderly with type 2 diabetes by the Markov modeling	Chao *et al* (2014)	Community services for diabetes	Health states	Treatment pathway Based on the results of a randomized controlled trial Variable health: –Severity of disease	Probability of a patients belonging to a given outcome state as time progresses	Not explicitly stated
Analytical methods featuring time dependence						
Intelligent patient management and resource planning for complex, heterogeneous, and stochastic healthcare systems	Garg *et al* (2012)	Integrated care system including hospital, social, and community services –Non-physical queues	Post hospital services	Patient groups: –Demographics –Care requirements –Length of stay	Forecast number of patients in post care outcome Forecast daily/total cost of care	Not explicitly stated
Improving health outcomes through better capacity allocation in a community–based chronic care model	Deo *et al* (2013)	Community care-for asthmatic patients –Non-physical queues	In service-appointment Waiting state Health states	Variable health Time between appointment Service capacity Health benefit of treatment	Optimised appointment allocation subject to health benefit and capacity	Not explicitly stated
Simulation analysis						
Evaluating multiple performance measures across several dimensions at a multi–facility outpatient center	Matta & Patterson (2007)	Outpatient services –Physical queues	Different services	Day of week Patient groups: –Care requirements Patient pathway Patient throughput Frequency of clinician overtime	Single parameter for analysing multiple, stratified performance measures Scenario analysis	Some suggested changes have been implemented

System dynamics analysis System dynamics is a modelling method whereby computer simulations of complex systems can be built and used to design more effective policies and organisations (Sterman, 2000). Two applications were found, modelling systems of markedly different sizes. Taylor *et al* (2005) evaluated the uses of community care services to bolster acute cardiac services whilst Wolstenholme (1999) evaluated the UK's NHS.

States were defined as community or acute services (Taylor *et al*, 2005) and different sectors of care, namely primary, acute, NHS continuing care and community care (Wolstenholme, 1999).

Capacity and rate variables, such as waiting list size and clinical referral guidelines were considered to influence flow within both models. A feedback mechanism was used by Taylor *et al* (2005) to evaluate how changes in these variables may stimulate and effect demand.

The main metrics of these models related to demand and access, namely waiting times and patient activity – for example, long-run use of services and length of queues (Wolstenholme, 1999). In both papers, a scenario analysis was performed to evaluate how changes within the model affected its output.

Wolstenholme (1999) reported that some findings were shared with NHS staff.

Analytical methods including time dependence Applications of analytical methods with time dependence included specialist clinics (Deo *et al*, 2013, Izady, 2015), care after discharge from an acute stroke unit (Garg *et al*, 2012), long-term institutional care (Xie *et al*, 2005, 2006), community mental health services (Utley *et al*, 2009; Pagel *et al*, 2012) and home/community care in British Columbia (Hare *et al*, 2009).

The state definitions within these models related to stages of care/different services (Xie *et al*, 2005, 2006; Hare *et al*, 2009; Utley *et al*, 2009; Pagel *et al*, 2012; Garg *et al*, 2012); "waiting" or "in service" (Deo *et al*, 2013; Izady, 2015) and health states – in particular stages of health progression (Deo *et al*, 2013) or post-care outcomes (Garg *et al*, 2012).

The factors considered to influence flow included capacity of services (Pagel *et al*, 2012, Izady, 2015); patient demographics and care requirements (Xie *et al*, 2005, 2006; Hare *et al*, 2009; Garg *et al*, 2012); patient health between recurrent appointments (Deo *et al*, 2013) and the length of time in which a person occupied a state (Utley *et al*, 2009).

Commonly, the system metrics used in these papers related to the time a patient spent interacting with parts of the system – such as expected length of stay, waiting times and time spent in states. Garg *et al* (2012) calculated the daily cost of care and likely post-care outcome states for patients of different demographic groups. Pagel *et al* (2012) and Deo *et al* (2013) identified optimal capacity allocations subject to desired levels of queue lengths and wait times, and impact on patient health, respectively. Hare *et al* (2009) evaluated the possible future demand for services under different scenarios and situations.

Of these applications, Pagel *et al* (2012) and Utley *et al* (2009) reported steps towards implementation. In the former, a software tool was created, whilst in the latter the findings of the model were shared with key stakeholders. Hare *et al* (2009) also noted the use of their model for care planning within their given setting.

Simulation methods The settings of these papers included long-term care (Cardoso *et al*, 2012; Zhang *et al*, 2012; Zhang and Puterman, 2013), outpatient services (Clague *et al*, 1997; Swisher & Jacobson, 2002; Matta & Patterson, 2007; Chand *et al*, 2009; Ponis *et al*, 2013; Pan *et al*, 2015), primary care and ambulatory clinics (Santibáñez *et al*, 2009; Fialho *et al*, 2011; Shi *et al*, 2014) and provisions of integrated acute and community services (Bayer *et al*, 2010; Patrick *et al*, 2015; Qiu *et al*, 2016).

States were defined as different services, clinics or sectors of care; or healthcare tasks within single clinics (Clague *et al*, 1997; Swisher & Jacobson, 2002; Santibáñez *et al*, 2009; Chand *et al*, 2009; Fialho *et al*, 2011; Shi *et al*, 2014). Chand *et al* (2009) and Pan *et al* (2015) modelled the flow of patient information alongside patient flow and thus defined states of information flow.

Factors considered to influence flow commonly included the healthcare requirements/demographics of patients (Clague *et al*, 1997; Swisher & Jacobson, 2002; Chand *et al*, 2009; Fialho *et al*, 2011; Shi *et al*, 2014), constrained capacity and rates of no show/reneging (Clague *et al*, 1997; Swisher & Jacobson, 2002; Shi *et al*, 2014). Bayer *et al* (2010), Cardoso *et al* (2012), Ponis *et al* (2013) and Qiu *et al* (2016) considered monetary influences such as budgetary constraints, cost of care and profitability. Chand *et al* (2009) used the variability of time in completing care tasks.

Common metrics related to the time that a patient spent waiting in a state or in the system as whole. Optimised capacity levels relating to key performance measures were also widely considered (Zhang *et al*, 2012; Zhang and Puterman, 2013; Ponis *et al*, 2013). Matta & Patterson (2007) calculated a single system metric – an aggregate of multiple performance measures stratified by day, facility routing and patient group. This single metric was formed of measures such as average throughput, average system time and average queue time.

The implementation of suggested changes was recorded in several applications (Clague *et al*, 1997; Matta & Patterson, 2007; Chand *et al*, 2009; Santibáñez *et al*, 2009; Zhang *et al*, 2012; Pan *et al*, 2015; Shi *et al*, 2014).

Papers found within the "Patient flow and outcomes" search

Markovian models As outlined in Tables 5 and 6, seven publications used Markovian methods and outcomes, two of which were also included within the "Patient flow within community care" section. The five new papers modelled transplant waiting lists (Zenios, 1999; Wang, 2004; Drekic *et al*, 2015), intensive care units (Shmueli *et al*, 2003) and emergency care (Kim and Kim, 2015).

In these models, states related to whether patients were "waiting" or had obtained a service/transplant. Drekic *et al* (2015) defined patient priority states to reflect health deterioration.

The factors that influenced flow related to patient health with groups or states used to assign priorities (Wang, 2004; Drekic *et al*, 2015) or, represent patient demographics and care requirements. The reneging characteristics of different groups of patients were also

Table 6 Papers included from "patient flow and outcomes" search only

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Markovian models						
Modeling the transplant waiting list: A queueing model with reneging	Zenios (1999)	Waiting list-transplant -Non-physical queues	Waiting list Obtained transplant	Patient groups: -Demographic -Transplant type Organ groups Reneging - death	Wait time in system and until transplant-per group Fraction of patients who receive transplant per group	Not explicitly stated
Optimizing admissions to an intensive care unit	Shmueli *et al* (2003)	Intensive Care Unit -Physical queues	ICU beds Waiting for service In service	Variable health: -Survival probability Capacity-beds Loss model	Expected number of statistical lives saved by implementing an outcome based admission policy	Not explicitly stated
Modeling and analysis of high risk patient queues	Wang (2004)	Waiting list-transplant -Non-physical queues	Waiting list Obtained transplant	Patient priority: -Health related Risk of death List size	Queue lengths and wait time-per group Expected number of deaths	Not explicitly stated
Differentiated waiting time management according to patient class in an emergency care center using an open Jackson network integrated with pooling and prioritizing	Kim and Kim (2015)	Emergency care centre -Physical queues	Waiting for service In service	Patient groups: -Acuity level Admission policy Patient group pooling Infinite waiting space	Waiting time -FCFS -Hybrid (FCFS and priority) -Hybrid with pooled groups	None explicitly stated
A model for deceased–donor transplant queue waiting times	Drekic *et al* (2015)	Waiting list-transplant -Non-physical queues	Waiting list Obtained transplant Patient priority -Health related	Variable health Prioritisation Reneging List size Blocking probability	Queue length and wait time Reneging probabilities-per group	Not explicitly stated
Non-Markovian steady state analysis						
Efficiency and welfare implications of managed public sector hospital waiting lists	Goddard & Tavakoli (2008)	Waiting list-hospital care -Non-physical queues	Number of people on the waiting list	Service capacity Rationing system Proportion of sick patients admitted	Wait time -All patients -For least ill patients	Not explicitly stated
A multi-class queuing network analysis methodology for improving hospital emergency department performance	Cochran & Roche (2009)	Emergency department -Physical queues	Stages of care	Patient group: -Care requirements Seasonality Number of beds	Queue lengths and wait time Service utilisation Requirements for a desired level of utilisation	Software made available to EDs Feedback to clinicians and ED managers

Table 6 (Continued)

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
A queueing model to address wait time inconsistency in solid–organ transplantation	Stanford *et al* (2014)	Waiting list-transplant -Non-physical queues	Waiting list Obtained transplant	Patient groups: -Care requirements Organ groups Compatibility	Wait time per patient type	Not explicitly stated
System dynamics analysis						
Modeling chronic disease patient flows diverted from emergency departments to patient–centered medical homes	Diaz *et al* (2015)	Care for chronic disease	Stages of care -Emergency departments -Ambulatory services	Patient groups: -Insured and uninsured -Care requirements Resource capacity Death Congestion	Scenario analysis Impact on demand for services and required capacity Resource utilisation Cost Health impact	Not explicitly stated
Analytical methods featuring time dependence						
Dynamic allocation of kidneys to candidates on the transplant waiting list	Zenios & Wein (2000)	Waiting list-transplant -Non-physical queues	Transplant queue Obtained transplant	Variable health Patient demographic Organ groups Availability of organ Transplant failure/re-join Quality of life measure	Wait time in system and until transplant -per group Fraction of patients who receive transplant per group	Not explicitly stated
The optimal timing of living-donor liver transplantation	Alagoz *et al* (2004)	Waiting list-transplant -Non-physical queues	Waiting list Obtained transplant Health states -Transplant in time period -Waiting in time period	Variable health Organ quality Post–transplant survival rate	Optimal timing of transplant	Not explicitly stated
A model for managing patient booking in a radiotherapy department with differentiated waiting times	Thomsen & Nørrevang (2009)	Radiotherapy -Non-physical queues	Radiotherapy slots	Patient groups: -Care requirements -Waiting time guarantee Capacity	Lower and upper limits for slot allocation per group	Suggested use within department

Table 6 *(Continued)*

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Investigating hospital heterogeneity with a multi-state frailty model: application to nosocomial pneumonia disease in intensive care units	Liquet *et al* (2012)	Intensive care	Admission Infection Death Discharge	Patient groups: -Frailty -Type of admission -Infection	Number of patients with infection -Death -Discharge	None explicitly stated
Optimizing intensive care unit discharge decisions with patient readmissions	Chan *et al* (2012)	Intensive care -Non-physical queues	ICU beds Number of people in the system	Variable health Demand driven discharge -Cost such as loss in QUALY Congestion	Optimisation of cost incurred by demand dependent discharge Readmission load and mortality rates -Low congestion -High congestion	Not explicitly stated
Planning for HIV screening, testing, and care at the veterans health administration	Deo *et al* (2015)	Community care-for HIV patients -Non-physical queues	Stages of care Health states	Variable health Allocation of screening Budgetary constraints Service constraints	Optimal screening policy with regards to health benefit, budget and capacity Staffing levels	Several suggestions influenced decision making
Radiation Queue: meeting patient waiting time targets	Li *et al* (2015)	Radiotherapy -Non-physical queues	Types of treatment slot for radiotherapy machines	Patient groups: –Care requirements -Service times Capacity Patient pooling	Required capacity to meet set waiting time targets Optimal allocation of capacity for different patient groups Utilisation	Not explicitly stated
Simulation analysis						
Simulating hospital emergency departments queuing systems: $(GI/G/m(t)):(IHFF/N/\infty)$	Panayiotopoulos & Vassilacopoulos (1984)	Emergency department-Physical queues	Waiting list In service	Variable clinician capacity Waiting capacity Variable patient priority:- Health related	Average number of patients-in system and queue Average time-in system and queue	Some suggested changes have been implemented
Development of a Central Matching System for the Allocation of Cadaveric Kidneys: A simulation of Clinical Effectiveness versus Equity	Yuan *et al* (1994)	Transplant waiting list -Non-physical queues	Waiting list Received transplant	Patient groups Organ groups Compatibility Availability of organs Time spent waiting	Assessment of different allocation algorithms -Time until transplant -Time waiting if no transplant by year end Number of unused organs	Not explicitly stated

Table 6 *(Continued)*

Title	*Authors*	*Setting*	*States*	*Factors considered to influence flow*	*Method output*	*Implementation of results*
Patient flows and optimal health-care resource allocation at the macro-level: a dynamic linear programming approach	van Zon & Kommer (1999)	General method for resource allocation	Stages of care Health states	Variable health Duration of medical activity Patient pathway Health benefit	Scenario analysis Optimisation of resources: -Health of patients -Wait time	Not explicitly stated
A simulation model to investigate the impact of cardiovascular risk in renal transplantation	McLean & Jardine (2005)	Waiting list-transplant -Non-physical queues	Waiting list Obtained transplant	Transplant failure Patient mortality rate Patient characteristics: -Demographics -Health risk	Post-transplant survival rate Scenario analysis	Not explicitly stated
A clinically based discrete-event simulation of end-stage liver disease and the organ allocation	Shechter *et al* (2005)	Waiting list-transplant -Non-physical queues	Waiting list Obtained transplant	Patient characteristics: -Demographics -Care requirements Organ type Variable health Graft failure	Post-transplant survival rate -1 year -3 year	Not explicitly stated
Capacity planning for cardiac catheterization: a case study	Gupta *et al* (2007)	Cardiac catheterization clinic -Physical queues	Stages of care	Patient group: -Care requirements Clinician case load	Wait times Optimised capacity allocation subject to desired wait times Scenario analysis	Some suggested changes have been implemented
A discrete event simulation tool to support and predict hospital and clinic staffing	DeRienzo *et al* (2016)	Neonatal intensive care -Physical queues	Intensive care beds	Patient groups: -Admission type -Acuity -Health Resource capacity	Estimated staffing allocation Forecast future demand Cost of provision	Not explicitly stated

considered in each transplant paper with patients modelled as leaving the waiting list due to death or for other reasons. (Zenios, 1999; Drekic *et al*, 2015).

The output measures of these papers commonly related to the wait time faced by patients. Other metrics included the probability of reneging per patient group (Drekic *et al*, 2015) and the expected number of deaths for waiting patients (Wang, 2004) or lives saved by an admission policy (Shmueli *et al*, 2003). Zenios (1999) calculated the average time spent in the system and in the queue for each demographic group, and the fraction of patients from each group who received a transplant.

None of the papers reported an implementation of their results within their care setting.

Non-Markovian steady-state models The modelled settings and applications included an emergency department (Cochran & Roche, 2009) and two waiting lists, one for hospital care (Goddard & Tavakoli, 2008), the other for transplant patients (Stanford *et al*, 2014). States were defined as stages of hospital care and as "waiting" or "in service".

The factors considered to influence flow were patient group and seasonality (Cochran & Roche, 2009) and resource availability and patient health (Goddard & Tavakoli, 2008; Stanford *et al*, 2014). Each model used metrics relating to the amount of time a patient spent within parts of the system.

Cochran & Roche (2009) reported an implementation of their results with software developed and made available for clinicians and care managers. Feedback and educational sessions were also organised to help key stakeholders to understand the work.

System dynamics analysis Diaz *et al* (2015) evaluated patient flow between states of acute care and home care for patients with chronic disease. The factors considered to influence flow related to patient groups based on their care requirements and whether they possessed insurance. Congestion and capacity of resources were also considered. A scenario analysis was performed to evaluate the impact of different patient routes and resource allocations on the level of demand for services and the cost of providing care.

Analytical methods including time dependence Nine papers were found, two of which were included in the "Patient flow within community care" section. Of the seven remaining, the settings were care for chronic diseases (Deo *et al*, 2015), two intensive care models (Liquet *et al*, 2012; Chan *et al*, 2012), two radiotherapy models (Thomsen & Nørrevang, 2009; Li *et al*, 2015) and two transplant waiting lists (Zenios & Wein, 2000; Alagoz *et al*, 2004).

States were defined as "in service" or "waiting", different services or different appointment slots (Thomsen & Nørrevang, 2009; Li *et al*, 2015). Alagoz *et al* (2004), Liquet *et al* (2012) and Deo *et al* (2015) also defined multiple health states.

The factors considered to influence flow were commonly related to differences within the patient population pertaining to health (Alagoz *et al*, 2004; Deo *et al*, 2015); care requirements or demographic/health-related groups (Zenios & Wein, 2000) and the availability of resources such as organs (Zenios & Wein, 2000; Alagoz *et al*, 2004) or appointment slots (Thomsen & Nørrevang, 2009; Deo *et al*, 2015, Li *et al*, 2015).

Common metrics used by these methods focussed on the amount of time a patient spent waiting for a service – for example, the optimal timing of appointments (Deo *et al*, 2015) or transplants (Alagoz *et al*, 2004) subject to changes in patient health. Zenios & Wein (2000) calculated output measures for different groups of patients to evaluate equity within the process of organ allocation. Forecasts of capacity requirements and optimal allocation of resources based on patient groups were also common.

Thomsen & Nørrevang (2009) and Deo *et al* (2015) reported that some of their suggestions had influenced decision making.

Simulation methods Eight applications were found with one included in the "Patient flow within community care" (Matta & Patterson, 2007). Of the seven remaining, applications included a cardiac catheterisation clinic (Gupta *et al*, 2007), three transplant waiting lists (Yuan *et al*, 1994; McLean & Jardine, 2005; Shechter *et al*, 2005), an evaluation of an emergency department (Panayiotopoulos & Vassilacopoulos, 1984), neonatal intensive care (DeRienzo *et al*, 2016) and a healthcare resource allocation model (van Zon & Kommer, 1999).

Within these papers, states were defined as healthcare tasks (van Zon & Kommer, 1999; Gupta *et al*, 2007), number of beds and "waiting" or "in service".

The factors considered to influence flow within these models included demographics/care requirements (van Zon & Kommer, 1999; McLean & Jardine, 2005; Shechter *et al*, 2005; Gupta *et al*, 2007); the health, mortality and survival rates of patients (van Zon & Kommer, 1999; McLean & Jardine, 2005; Shechter *et al*, 2005) and resource capacity.

Several metrics were calculated within these methods, with the time patients spent interacting with or waiting within parts of the system a common measure. Other outputs of interest included capacity allocation (Yuan *et al*, 1994; Gupta *et al*, 2007; DeRienzo *et al*, 2016); the cost of care, health benefits of service (van Zon & Kommer, 1999) and the expected survival rate of patients (McLean & Jardine, 2005; Shechter *et al*, 2005).

Panayiotopoulos & Vassilacopoulos (1984) and Gupta *et al* (2007) both noted that some of their suggested changes had been implemented.

Summary of findings and discussion across literatures

Findings from across the literature will now be summarised and discussed, drawing together common themes and key characteristics as presented in Tables 4, 5 and 6. In combination, we reviewed 53 papers presenting models of patient flow. 30 applied to community care services which included mental health services, physical health services, outpatient care and patient flow within acute and community settings. Furthermore, 32 applications used, in some form, either queue lengths or the amount of time that a patient spent within states as output measures. The next most common metrics were monetary costs in relation to patient use and the allocation of capacity-related resources.

Within the "Patient flow and community care" literature a range of flow characteristics were considered. For instance, patients access and arrivals to community services were modelled as unscheduled (e.g. Taylor *et al*, 2005), by appointment (e.g. Deo *et al*, 2013, 2015), by external referral (e.g. Koizumi *et al*, 2005), or a mixture of the above (e.g. Chand *et al*, 2009; Song *et al*, 2012). Furthermore, multiple care interactions were modelled as either sequential visits to different services (e.g. Koizumi *et al*, 2005; Song *et al*, 2012) or as single visits where multiple tasks were carried out (e.g. Chand *et al*, 2009). In either instance patients were sometimes modelled as being able to recurrently visit the same service over time with some patients using the service more frequently (e.g. Shi *et al*, 2014; Deo *et al*, 2013).

Within the "Patient flow and outcome" literature, there were 10 models of transplant/waiting lists, 8 of community, ambulatory and outpatient services, 3 of emergency departments, 4 for intensive care, 2 for radiotherapy and 1 general model of resource allocation. Outcome measures were incorporated within the outputs of these models in three broad ways: (1) system metrics were stratified by outcome related groups; (2) variable patient or population level health was used as an objective or constraint within a model to influence resource allocation or (3) health outcomes – such as patient mortality or future use of care – were used as system metrics. Notably, 15 papers used patient groups to represent differing health/outcomes, whilst 13 papers incorporated variable health/outcome which could change during a course of care. By including variable health/outcome, a model's output was informed by the effect of a care interaction, or absence of a care interaction, on patient outcomes and on the operation of the system.

Patient groups relating to health/outcome were used in models of each method and were commonly used in resource and service capacity allocations. Notably, their application within steady-state methods is limited since it is difficult to model differing group-dependent variables, such as service times, since the order of patients within these queues is unknown.

Variable health/outcome which could change during a course of care was commonly used within time-dependent methods. They were used to model the effect of care on a population where the modelled time period was large, such as stays with residential care or where multiple interactions were considered.

Across both literatures, queues could be categorised as either physical – constrained demand – or non-physical – unconstrained demand, as per Tables 4, 5 and 6. Physical queues form when patients wait for service within a fixed physical space. Examples include, arrivals forming a queue within a clinic or emergency care (e.g. Chand *et al*, 2009; Santibáñez *et al*, 2009; Shi *et al*, 2014) or when patients move between care interactions and immediately wait within another single physical location (e.g. Xie *et al*, 2005, 2006; Cochran & Roche, 2009). When physical queues occur, the time a patient spends waiting for service is typically of the order of their expected service time. These queues are constrained and patient demand is modelled from the point when they physically arrive to the service.

Given these dynamics, the most common analysis of physical queues related to the daily operation of single services. Such models were used to gain insight into the delivery of care (e.g. flow between multiple treatments/consultations in a single visit). Studies of physical queues were carried out using each type of method. The choice of method depended on the desired insight, factors considered to influence flow and size of the system. Steady-state methods were sufficient if queue lengths and wait times were of primary concern. However, if variability in input parameters or periodic influences were important, time variable methods were more appropriate. These models typically focus on shorter time frames of care, therefore health/outcome groups were used within these models.

Alternatively, non-physical queues occur when patients may wait in any location away from the service such as their place of residence-e.g. when care is scheduled (Deo *et al*, 2013) or a patients wait is potentially long and unknown (Zenios & Wein, 2000). Non-physical queues represent unconstrained demand which begins from the point when a patient is referred to a service. A patient's wait is therefore typically of an order larger than their expected service time. Such models are commonly used to model the demand and access at a system level.

The most common analysis of non-physical queues related to waiting lists and multiple uses of a single or multiple services. Studies of these scenarios were carried out using steady-state analysis or time-dependent methods. Due to the long-run nature of steady-state models these models were appropriate for such situations, especially when variability and differences within the patient population were negligible. In scenarios of scarce appointment or resource allocation, time variable methods were increasingly used. Within these models, variable health/outcome was widely considered due to the longer time frames of care, possible multiple interactions and the benefits stated previously.

It should be noted that this work is limited due to the difficulty of systematically reviewing this literature. In particular, we found two main difficulties. Firstly, these papers are published within a wide range of journals, some within healthcare journals, others in operational research (OR) journals, whilst a proportion was found within journals that were neither health-specific nor OR specific. Secondly, we found that patient flow is described and referred to in myriad ways within literature. No clear standards were found; thus, locating these papers was particularly difficult.

Due to the complexity of finding literature, we cannot claim our findings to be exhaustive. However, by following an iterative process of literature searching our findings are representative of this literature, allowing us to draw meaningful conclusions in the next section.

As a final observation, the reporting of implementation and collaboration varied greatly within each group of analytical method.

Conclusions and directions for future work

Community healthcare consists of a diverse range of geographically disparate services, each providing treatment to patients with specific health needs. As a result, the factors that are considered to influence patient flow are often markedly different to acute services and vary from one service to another. Considering the characteristics discussed in this review, it is common for a mixture of complex dynamics to be modelled within community care applications. Modelling these services can thus become complicated, requiring innovative methods to include all or some of these dynamics. This is highlighted by the range of different methods presented in this review.

Future directions for patient flow modelling within community care are now explored motivated by known challenges for community care, gaps found within the literature and any transferable knowledge between the two sets of literature.

Few models considered patient flow within systems of differing community services with most studies focussing on single services. Likewise, few also considered the mix of patients within these services. Consider, however, a diabetes pathway where patients may require treatment for comorbidities from multiple services based in the community. Each of these services will also provide care to a range of patients, not just those with diabetes. This example highlights a significant challenge in the management of community services. Namely, how to co-ordinate and deliver care within physically distributed, co-dependent services considering increasing episodic use by patients with differing needs. With a shift of focus towards care for the increasing number of patients with multiple long-term illnesses (NHS England, 2014), the patient mix within each service further exacerbates this challenge. Therefore, it would be beneficial to develop methods for modelling patient flow through multiple services to investigate these scenarios.

Considering the above, another useful direction would be to develop time-dependent analytical methods and simulation models for these scenarios. Whilst often analytically difficult, there are important benefits in using these methods as shown by the wide range of applications within this review. Given the characteristics of community services previously discussed, a helpful addition to the research landscape would be models of systems for which steady-state assumptions do not hold or where capacity, demand and timing of patient use vary. This would be helpful in community care where – due to the decentralisation – it can be hard to measure and interpret the impact that changes to one part of the system have on the whole system over short-term and long-term time periods. In considering flow in a system of inter-related services, or situations where patients may re-use the same service over a time period, the development of system level, time-dependent methods would be beneficial in analysing the time variable impact of changes in the immediate, short term and long term for the whole system.

Finally, 13 papers used variable health/outcomes, of which 5 applied to multiple care interactions. Again considering the purpose and nature of community care, we suggest that methods which use multiple health states to model the improvement and decline of patient health throughout a course of care would be a useful direction for future study. A good example of these methods is presented by Deo *et al* (2013, 2015). Having otherwise not been widely explored, methods that quantify and evaluate the quality of care and include an interaction between patient outcomes, care pathways and flow within the system would be valuable and appropriate for community care modelling.

In considering OR methods for community services which combine patient flow modelling and patient outcomes, there may be some transferable knowledge from transplant models. For situations where non-physical are modelled, transplant list models may provide a useful basis as they share some distinct similarities to community care services – such as reneging, time-varying demand, limited resources and in some cases re-entrant patients. Transplant models may be informative for both scheduled care and unscheduled care.

Acknowledgements

This research was supported by the National Institute for Health Research (NIHR) Collaboration for Leadership in Applied Health Research and Care North Thames at Barts Health NHS Trust. The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR or the Department of Health. The first author was supported by the Health Foundation as part of the Improvement Science PhD programme. The Health Foundation is an independent charity committed to bringing about better health and healthcare for people in the UK.

References

Alagoz O, Maillart LM, Schaefer AJ and Roberts MS (2004) The optimal timing of living-donor liver transplantation. *Management Science* **50**(**10**), 1420–1430.

Bayer S, Petsoulas C, Cox B, Honeyman A and Barlow J (2010) Facilitating stroke care planning through simulation modelling. *Health Informatics Journal* **16**(**2**), 129–143.

Bhattacharjee P and Ray PK (2014) Patient flow modelling and performance analysis of healthcare delivery processes in hospitals: a review and reflections. *Computers & Industrial Engineering* **78**, 299–312.

Bretthauer KM and Côté MJ (1998) A model for planning resource requirements in health care organizations. *Decision Sciences* **29**(**1**), 243–270.

Cardoso T, Oliveira MD and Barbosa-póvoa A (2012) Modeling the demand for long-term care services under uncertain information. *Health Care Management Science* **15**(**4**), 385–412.

Cayirli T, Veral E and Rosen H (2006) Designing appointment scheduling systems for ambulatory care services. *Health Care Management Science* **9**(**1**), 47–58.

Chan CW, Farias VF, Bambos N and Escobar GJ (2012) Optimizing intensive care unit discharge decisions with patient readmissions. *Operations Research* **60**(**6**), 1323–1341.

Chand S, Moskowitz H, Norris JB, Shade S and Willis DR (2009) Improving patient flow at an outpatient clinic: study of sources of variability and improvement factors. *Health Care Management Science* **12**(**3**), 325–340.

Chao J *et al* (2014) The long-term effect of community-based health management on the elderly with type 2 diabetes by the Markov modeling. *Archives of Gerontology and Geriatrics* **59**(**2**), 353–359.

Clague JE, Reed PG, Barlow J, Rada R, Clarke,M and Edwards RHT (1997) Improving outpatient clinic efficiency using computer simulation. *International Journal of Health Care Quality Assurance* **10**(**5**), 197–201.

Cochran JK and Roche KT (2009) A multi-class queuing network analysis methodology for improving hospital emergency department performance. *Computers & Operations Research* **36**(**5**), 1497–1512.

Côté MJ (2000) Understanding patient flow. *Decision Line* **31**(**2**), 8–10.

Deo S, Iravani S, Jiang T, Smilowitz K and Samuelson S (2013) Improving health outcomes through better capacity allocation in a community-based chronic care model. *Operations Research* **61**(**6**), 1277–1294.

Deo S, Rajaram K, Rath S, Karmarkar US and Goetz MB (2015) Planning for HIV screening, testing, and care at the Veterans Health Administration. *Operations Research* **63**(**2**), 287–304.

Derienzo CM, Shaw RJ, Meanor P, Lada E, Ferranti J and Tanaka D (2016) A discrete event simulation tool to support and predict hospital and clinic staffing. *Health Informatics Journal*, 1460458216628314.

Diaz R, Behr J, Kumar S and Britton B (2015) Modeling chronic disease patient flows diverted from emergency departments to patient-centered medical homes. *IIE Transactions on Healthcare Systems Engineering* **5**(**4**), 268–285.

Drekic S, Stanford DA, Woolford DG and Mcalister VC (2015) A model for deceased-donor transplant queue waiting times. *Queueing Systems* **79**(**1**), 87–115.

England NHS (2014) *Five Year Forward View*. London: HM Government.

Fialho AS, Oliveira MD and Sa AB (2011) Using discrete event simulation to compare the performance of family health unit and primary health care centre organizational models in Portugal. *BMC Health Services Research* **11**, 274.

Garg L, McClean S, Barton M, Meenan BJ and Fullerton BJ (2012) Intelligent patient management and resource planning for complex, heterogeneous, and stochastic healthcare systems. *IEEE Transactions on Systems, Man, and Cybernetics Part A: Systems and Humans* **42**(**6**), 1332–1345.

Goddard J and Tavakoli M (2008) Efficiency and welfare implications of managed public sector hospital waiting lists. *European Journal of Operational Research* **184**(**2**), 778–792.

Gough D, Thomas J and Oliver S (2012) Clarifying differences between review designs and methods. *Systematic Reviews* **1**, 28.

Gupta D *et al* (2007) Capacity planning for cardiac catheterization: a case study. *Health Policy* **82**(**1**), 1–11.

Hare WL, Alimadad A, Dodd H, Ferguson R, Rutherford A (2009) A deterministic model of home and community care client counts in British Columbia. *Health Care Management Science* **12**(**1**), 80–98.

Hensher M (1997) Improving general practitioner access to physiotherapy: a review of the economic evidence. *Health Services Management Research* **10**(**4**), 225–230.

Hulshof PJH, Kortbeek N, Boucherie RJ, Hans EW and Bakker PJM (2012) Taxonomic classification of planning decisions in health care: a structured review of the state of the art in OR/MS. *Health Systems* **1**, 129–175.

Izady N (2015) Appointment capacity planning in specialty clinics: a queueing approach. *Operations Research* **63**(**4**), 916–930.

Kim S and Kim S (2015) Differentiated waiting time management according to patient class in an emergency care center using an open Jackson network integrated with pooling and prioritizing. *Annals of Operations Research* **230**(**1**), 35–55.

Koizumi N, Kuno E and Smith TE (2005) Modeling patient flows using a queuing network with blocking. *Health Care Management Science* **8**(**1**), 49–60.

Kucukyazici B, Verter V and Mayo NE (2011) An analytical framework for designing community-based care for chronic diseases. *Production and Operations Management* **20**(**3**), 474–488.

Li S, Geng N and Xie X (2015) Radiation queue: meeting patient waiting time targets. *IEEE Robotics and Automation Magazine* **22**(**2**), 51–63.

Liquet B, Timsit JF and Rondeau V (2012) Investigating hospital heterogeneity with a multi-state frailty model: application to nosocomial pneumonia disease in intensive care units. *BMC Medical Research Methodology* **12**(**1**), 1.

Matta ME and Patterson SS (2007) Evaluating multiple performance measures across several dimensions at a multi-facility outpatient center. *Health Care Management Science* **10**(**2**), 173–194.

McLean DR and Jardine AG (2005) A simulation model to investigate the impact of cardiovascular risk in renal transplantation. *Transplantation Proceedings* **37**(**5**), 2135–2143.

Moher D, Liberati A, Tetzlaff J and Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of Internal Medicine* **151**(**4**), 264–269.

Munton T, Martin A, Marrero I, Llewellyn A, Gibson K and Gomersall A (2011) Evidence: getting out of hospital? *The Health Foundation*.

Pagel C, Richards DA and Utley M (2012) A mathematical modelling approach for systems where the servers are almost always busy. *Computational and Mathematical Methods in Medicine*.

Pan C, Zhang D, Kon AWM, Wai SL and Ang WB (2015) Patient flow improvement for an ophthalmic specialist outpatient clinic with aid of discrete event simulation and design of experiment. *Health Care Management Science* **18**(**2**), 137–155.

Panayiotopoulos JC and Vassilacopoulos G (1984) Simulating hospital emergency departments queuing systems: $(GI/G/m(t)):(IHFF/N/\infty)$. *European Journal of Operational Research* **18**(*2*), 250–258.

Patrick J, Nelson K and Lane D (2015) A simulation model for capacity planning in community care. *Journal of Simulation* **9**(**2**), 111–120.

Ponis ST, Delis A, Gayialis SP, Kasimatis P and Tan J (2013). Applying discrete event simulation (DES) in healthcare: the case for outpatient facility capacity planning. *International Journal of Healthcare Information Systems and Informatics* **8**(**3**), 58–79.

Powell J (2002) Systematic review of outreach clinics to primary care in the UK. *Journal of Health Services Research and Policy* **7**(**3**), 177–183.

Qiu Y, Song J and Liu Z (2016) A simulation optimisation on the hierarchical health care delivery system patient flow based on multi-fidelity models. *International Journal of Production Research 54*(**21**), 6478–6493.

Santibáñez P, Chow VS, French J, Puterman ML. and Tyldesley S (2009) Reducing patient wait times and improving resource utilization at British Columbia Cancer Agency's ambulatory care unit through simulation. *Health Care Management Science* **12**(**4**), 392–407.

Shechter S M, *et al* (2005) A clinically based discrete-event simulation of end-stage liver disease and the organ allocation process. *Medical Decision Making* **25**(**2**), 199–209.

Shi J, Peng Y and Erdem E (2014) Simulation analysis on patient visit efficiency of a typical VA primary care clinic with complex characteristics. *Simulation Modelling Practice and Theory* **47**, 165–181.

Shmueli A, Sprung CL and Kaplan EH (2003) Optimizing admissions to an intensive care unit. *Health Care Management Science* **6**(**3**), 131–136.

Sibbald B, McDonald R and Roland M (2007) Shifting care from hospitals to the community: a review of the evidence on quality and efficiency. *Journal of Health Services Research and Policy* **12**(**2**), 110–117.

Song J, Chen W and Wang L (2012) A block queueing network model for control patients flow congestion in urban healthcare system. *International Journal of Services Operations and Informatics* **7**(**2**–**3**), 82–95.

Stanford DA, Lee JM, Chandok N and Mcalister V (2014) A queuing model to address waiting time inconsistency in solid-organ transplantation. *Operations Research for Health Care* **3**(**1**), 40–45.

Sterman JD (2000) *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston: McGraw-Hill.

Swisher JR and Jacobson SH (2002) Evaluating the design of a family practice healthcare clinic using discrete-event simulation. *Health Care Management Science* **5**(**2**), 75–88.

Taylor K, Dangerfield B and le Grand J (2005) Simulation analysis of the consequences of shifting the balance of health care: a system dynamics approach. *Journal of Health Services Research & Policy* **10**(**4**), 196–202.

Thomsen MS and Nørrevang O (2009) A model for managing patient booking in a radiotherapy department with differentiated waiting times. *Acta Oncologica* **48**(**2**), 251–258.

Utley M, Gallivan S, Pagel C and Richards D (2009) Analytical methods for calculating the distribution of the occupancy of each state within a multi-state flow system. *IMA Journal of Management Mathematics* **20**(**4**), 345–355.

van Zon AH and Kommer GJ (1999) Patient flows and optimal health-care resource allocation at the macro-level: a dynamic linear programming approach. *Health Care Management Science* **2**(**2**), 87–96.

Wang Q (2004) Modeling and analysis of high risk patient queues. *European Journal of Operational Research* **155**(**2**), 502–515.

Whitten PS, Mair FS, Haycox A, May CR, Williams TL and Hellmich S (2002) Systematic review of cost effectiveness studies of telemedicine interventions. *British Medical Journal* **324**, 1434–1437.

Wolstenholme E (1999) A patient flow perspective of UK health services: exploring the case for new" intermediate care" initiatives. *System Dynamics Review* **15**(**3**), 253–271.

Xie H, Chaussalet TJ and Millard PH (2005) A continuous time Markov model for the length of stay of elderly people in institutional long-term care. *Journal of the Royal Statistical Society: Series A (Statistics in Society)* **168**(**1**), 51–61.

Xie H, Chaussalet TJ and Millard PH (2006) A model-based approach to the analysis of patterns of length of stay in institutional long-term care. *IEEE Transactions on Information Technology in Biomedicine* **10**(**3**), 512–518.

Yuan Y, Gafni A, Russell JD and Ludwin D (1994) Development of a central matching system for the allocation of cadaveric kidneys a simulation of clinical effectiveness versus equity. *Medical Decision Making* **14**(**2**), 124–136.

Zenios SA (1999) Modeling the transplant waiting list: a queueing model with reneging. *Queueing Systems* **31**(**3**–**4**), 239–251.

Zenios SA and Wein LM (2000) Dynamic allocation of kidneys to candidates on the transplant waiting list. *Operations Research* **48**(**4**), 549–569.

Zhang Y, Berman O and Verter V (2009) Incorporating congestion in preventive healthcare facility network design. *European Journal of Operational Research* **198**(**3**), 922–935.

Zhang Y and Puterman ML (2013) Developing an adaptive policy for long-term care capacity planning. *Health Care Management Science* **16**(**3**), 271–279.

Zhang Y, Puterman ML, Nelson N and Atkins D (2012) A simulation optimization approach to long-term care capacity planning. *Operations Research* **60**(**2**), 249–261.

Received 8 June 2016;
revised 16 December 2016;
accepted 6 January 2017