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ORIGINAL ARTICLE

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Operational research applied to decisions in home health care: A systematic literature review

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ABSTRACT
The efficient deployment of resources in home-based care is considered crucial for the sustainability of health and social care systems worldwide. The aim of this study was to identify and review operational research approaches to support decision-making in home health care. We identified a set of linked decisions at different planning levels (strategic, tactical, operational) and conducted a systematic review of operational research approaches used to address these decisions. We also sampled OR literature applied to analogous decisions in other settings. The 77 papers selected focused predominantly on solutions for staff-to-patient allocation, visit scheduling and staff routing, few of which were adopted by organisations. Few studies dealt with tactical decisions of team size and composition or strategic decisions of districting, and we found no studies on contract design for commissioning home health care, on staff role definitions or on reassessment of patient need. Integrative work is scarce and the aspects of system performance considered are variable and diverse. For these reasons the literature does not provide guidance for home health care services aspiring to effective and coherent decisions across planning levels. OR approaches from other areas of application provide some insights for future research aimed at addressing this shortfall.

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KEYWORDS
OR in health services; home health care; systematic literature review

1. Introduction

Home health care (HHC) (the face-to-face delivery of care by a worker in a patient's or client's home) is seen as an important component of the health care sector and one that presents a distinct set of decision problems for those designing, funding, providing and working within such services (Hulshof et al., 2012). It can be argued that the importance of HHC is increasing due to its potential role in addressing two key policy initiatives within health and social care across many nations: reducing use of and stays within hospitals, and reducing demand for long-term residential care facilities by prolonging the time that people can live in their own home, including at the end of life (NHS England, 2014; Monitor, 2015).

As noted in Burgess (2012), patients, professionals and the organisations that commission or provide home health care may all have different notions of what improved system performance means to them. For instance, patients may value punctual visits or visits within preferred time windows, staff may value fair distribution of work within or between teams, and provider organisations may want to reduce the amount of unproductive time that staff spend travelling. The complexity of home health care and the relationships and potential trade-offs between such aspects of system performance make HHC amenable to operational research approaches.

The decision problems associated with HHC include logistic problems well studied within the Operational Research (OR) literature, and Cissé et al. (2017) and Fikar and Hirsch (2017) provide technical reviews of the state-of-the-art in routing and scheduling of HHC staff. While conceptually restricted to the delivery of health care services rather than personal social care, the blurred distinctions in different settings, and the scope for integration and coordination of some health and personal social care services delivered in the home mean that some literature is common to both. Other reviews by Gutiérrez and Vidal (2013) and Sahin and Matta (2015) map the extant literature onto a broader framework of decision problems related to the design and delivery of HHC services. These decision frameworks reflect the hierarchical nature of decisions in HHC from a supply chain perspective. Both reviews highlight that there is abundance of work in some operational domains and less work in strategic and tactical decision making. Another finding of both reviews is that there is little explicit recognition of this hierarchy within the papers they reviewed.

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The authors point out that this undermines the potential benefits of improved operational decision making by not making clear the strategic and tactical decisions required to create a context in which OR approaches to operational decisions can have most impact.

The research questions raised by these previous reviews include:

- What combinations and hierarchies of decisions have been addressed in the OR literature on home health care and what aspects system performance have been considered when addressing each decision?
- Can a group of research works be identified that, together, provide a comprehensive (in terms of the decisions addressed) and coherent (in terms of the aspects of system performance considered) set of OR solutions to decision problems for Home Health Care?
- What decisions relevant to home health care and amenable to OR have been given insufficient attention in the literature?

In this paper we address these research questions by:

- counting the numbers of papers that address different combinations and hierarchies of decision;
- reviewing how the performance of HHC systems is conceived within the literature and mapping the different aspects of system performance considered within the literature to the different decisions addressed;
- clustering papers by the aspects of performance considered and identifying the sets of decisions spanned within each cluster;
- comparing the set of decisions addressed in the literature to a hierarchical framework of decisions in HHC compiled with input from discussions with HHC decision makers in North East London.

As a secondary research question, we sought to identify OR approaches used outside HHC that could be adapted to address decision problems neglected by the set of papers identified in this review.

Our review has been undertaken as part of a study in which we are working with a number of home health care organisations. While these organisations face problems of districting, service definition, contract design and capacity planning, their efforts to improve efficiency focus largely on what they term as "workforce innovations", essentially changes to the work done by clinicians and how this work is organised. As well as including interventions to tackle operational decision problems addressed in the OR literature, these workforce innovations include interventions to increase the use of information technology to cut administration time and reduce the need for staff routes to start and/or end routes at a base, introducing new scoring systems intended to quantify workload more fairly, and considering the creation of new workforce roles. Some of these alter the nature of operational problems addressed in the literature and/or facilitate the implementation of OR solutions, whereas others frame their own decision problems. This motivated us to bring to the fore the explicit and implicit assumptions made in the literature about workforce structure, terms of employment, preferences and agency. We consider how these underpinning assumptions may influence the feasibility, acceptability or potential benefits associated with different OR approaches in the context of the workforce arrangements that prevail in different health care systems.

This work contributes to the body of operational research on home health care by updating previous reviews, providing an analysis of the extent to which the current OR literature provides a basis for improved, coherent decision making across the spectrum of decisions faced in home health care, and identifying priority areas for future research, in terms of decision problems to address and contextual and environmental features of home health care systems that should be reported alongside model formulations and solution approaches.

2. Methods

2.1. Decision problems in home health care

We identified an initial set of decisions at different planning levels relevant to the design and delivery of HHC from Hulshof et al. (2012). We split some of these into multiple decisions, for example Hulshoff's 'Visit (re-)scheduling' was separated into four discrete decisions, 'allocation of staff', 'visit scheduling', 'routing of visits' and 'short-term fixes', whilst acknowledging that sometimes these decisions are combined within modelling approaches in the literature.

We then broadened this based on discussions with HHC stakeholders in North East London, which comprised 29 meetings and 3 workshops with people working in the HHC system, including managers and frontline nursing staff from the local home health provider and commissioners of home health services, managers of local voluntary organisations providing support to home care patients and their families and a group of service user representatives. In relation to the set of decisions considered in this paper, our findings from these discussions led us to augment the frameworks of home health care decisions presented elsewhere in the literature in the following ways:

- Stakeholders are currently considering the introduction of new workforce roles that blend skills associated with multiple roles, including across different traditional professional disciplines (e.g. hybrid nursing and physio support roles). We therefore felt that defining workforce roles was a decision that needed to be differentiated from that of resource dimensioning or allocation (as used by Hulshof et al., 2012), which generally focus on determining the number of staff needed from existing roles.
- The development of home health care plans for patients is not explicitly covered by Hulshof et al. (2012) or previous reviews on HHC (e.g. Gutiérrez & Vidal, 2013; Sahin & Matta, 2015 and Cissé et al., 2017), but we found it to be an important decision that stakeholders face, which relates not only to operational decisions about scheduling visits but also to tactical decisions regarding team size and composition. Related to this, the timing and nature of reassessments of patient need, which feed into amendments to care plans, was also considered an important decision by stakeholders (and absent from Hulshof et al., 2012) and the frameworks presented in the previous reviews).
- Many patients receive multiple home-based health or care services and informal support, and stakeholders felt it was important to consider how these services can coordinate effectively. Although Sahin and Matta (2015) refer to decisions about partnership strategy at a strategic level and the identification of partners at a tactical level, they do not make explicit coordination with other services at an operational level, and this is also absent in Hulshoff's taxonomy (Hulshof et al., 2012) and the other HHC review articles (Gutiérrez & Vidal, 2013; Cissé et al., 2017).
- There are important patient-level service processes that feed into the decisions, such as identifying and specifying a patient's need(s), and some stakeholders focus primarily on the main patient-level output from the decisions, namely the delivery of a home visit. Therefore, in line with Gutiérrez and Vidal (2013), who include an explicit dimension on service processes in their framework, we added the decision inputs 'need identified' and 'referral' to our framework along with the decision output 'home visit'. We also made explicit the distinction between decisions and their inputs and outputs.

In addition to incorporating these findings into our framework, we identified logical links and hierarchical orderings between the decisions to ensure consistency with existing descriptions of HHC from a supply chain perspective (Gutiérrez & Vidal, 2013; Sahin & Matta, 2015). We then devised a graphical representation of this decision framework (Figure 1), in which we placed the output of a home visit on the right hand side of the page and then worked back through the decisions (and other inputs) necessary for a specific professional to visit a specific patient at a particular time on a particular day. This led to a group of operational decisions being placed in the centre of the page. Within this left-to-right flow of quasi-precedence relationships, we chose to display organisations' prior strategic and tactical decisions as feeding into operational decisions from above, with prior patient-specific decisions feeding into operational decisions from below. Both of these strands were considered to be dependent on a decision around the definition of service to be offered and the terms of access for patients, with this placed at the far left of the page.

Where possible, our working definition of each decision was made consistent with the nomenclature used in Hulshof et al. (2012).

2.2. Literature search

2.2.1. Operational research applied to home health care

We conducted a systematic review to assess the extent to which the development and adoption of OR approaches address the identified set of HHC decision problems.

We searched the electronic database Web of Science (https://wok.mimas.ac.uk/) using a combination of the search terms listed in Appendix 1 (Tables A1 and A2), and extracting records with:

- at least one of the terms related to OR methods set out in Table A1 in the article title, abstract or keywords (informed by Palmer et al. 2018);
  AND
- at least one of the terms related to the setting of HHC set out in Table A1 in the article title, abstract or keywords;
  AND
- at least one of the decision terms set out in Table A2 in the article title, abstract or keywords.

Note that our choice of search terms respected that the distinction between health care and social/personal care activities can differ among systems, meaning that some of the papers identified relate to

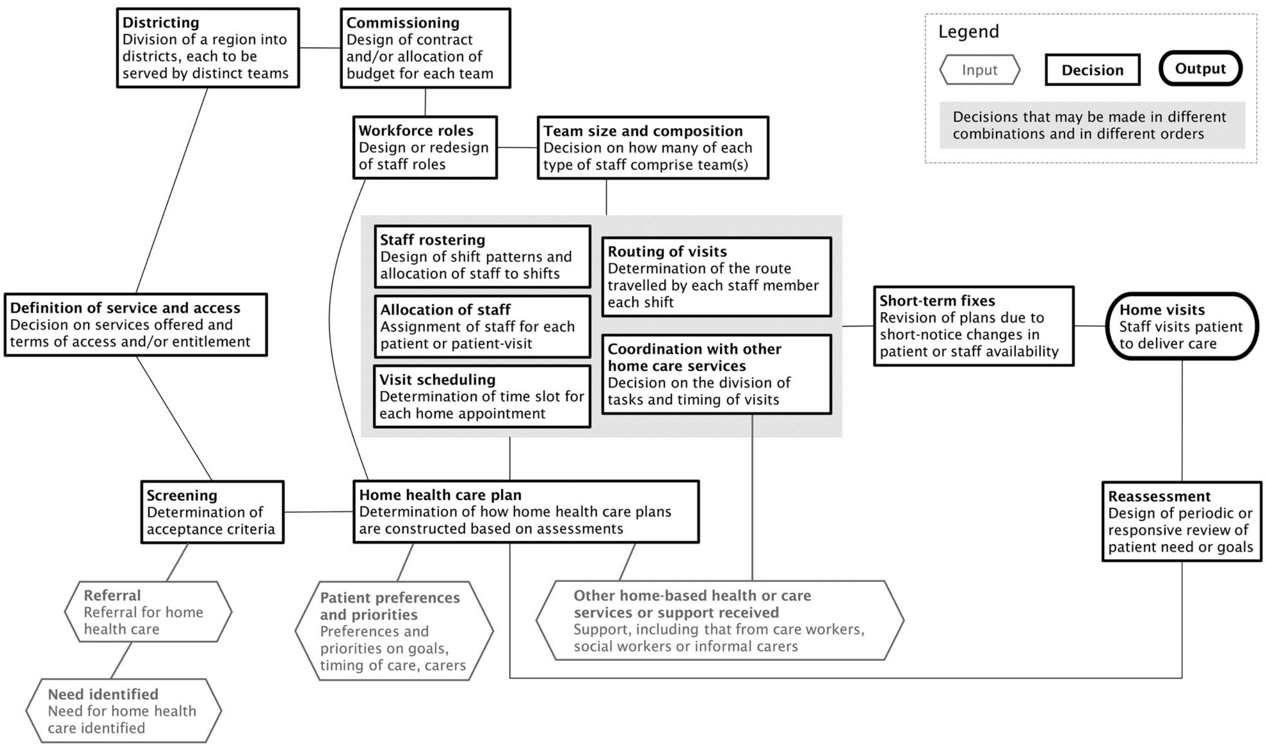

Figure 1. A graphical representation of the set of decision problems identified as associated with the design and operation of a home health care service. The framework diagram shows a flow of decisions from the definition of the service to delivery of care at a patient's home, with some key inputs related to the patient shown at the bottom.

the delivery of personal social care by non-health professionals.

We considered all publications in English with no constraints on publication type or year. The search was run on the 28th September 2018. All publications found were then assessed against this sequence of criteria:

- Peer-reviewed: The titles and abstracts of only peer-reviewed articles were assessed.
- Title/abstract: Review articles were subject to full text reading if the title and/or the abstract suggested that a subset of the papers reviewed focused on tackling decisions in HHC through OR approaches. Other publication types (e.g. research articles, peer-reviewed conference proceedings, book chapters) were subject to full text reading if the title and/or abstract suggested that the work focused on tackling one or more of the decisions of interest in HHC through an OR approach.
- Full text: Articles were retained if the above criterion was still satisfied on reading of the full text and, for non-review articles, if the description of the approach was sufficiently detailed to identify modelling assumptions, formulation and outputs.

Additional research papers identified from accepted review articles were then subject to the same sequence of inclusion criteria. We only extracted data from non-review article publication types.

2.2.2. Operational research applied to analogous decision problems

We conducted an additional scoping review of OR approaches to decisions analogous to those in HHC that have been developed for other settings outside HHC. To do this, we used the same search strategy described in 2.2.1 but without the "Settings" terms and with some HHC specific "Decision" terms adapted (for instance "nurse" was replaced with "worker" in searches – see Table A3 in Appendix 1 for full details). Defined this way, analogous decisions included, for example, the scheduling and routing of workers providing maintenance services at a number of client locations or the size and composition of teams in other industries. Because of this broad definition and the anticipated volume of papers related to some decisions, we restricted this scoping review to review articles. From the search results associated with each analogous decision, we studied the two most recent review articles describing decision problems where we considered the structure of the problem and the nature of objectives/requirements to be similar to those we found in HHC settings.

2.3. Data extraction

The study team agreed on an initial data extraction table for the systematic review. Data extracted included the aim of the study, the HHC decisions addressed, the planning horizon considered, the modelling and solution approaches taken, the aspects of performance considered (and associated metrics) and the level of engagement with practice. One reviewer (LG) carried out the article search and selection, reading and data extraction, making an initial assessment as to the decision(s) in HHC addressed. In cases where the same aspect of performance was labelled differently in different publications (e.g. "caregiver utilisation", "worker utilisation", "resource utilisation"), we chose a label (e.g. "staff utilisation") for our analyses. For papers in which the aspects of HHC system performance being promoted were not explicit, a judgement was made based on the objective functions and constraints of models and on the presentation of results.

To identify and to try to minimise the impact of subjective assessments in extracting data, a second reviewer (MU) read 20% of the selected papers sampled at random but with at least one paper per decision where possible. Data extracted by the second reader was compared with that obtained from first reading. Any systematic difference in extraction or interpretation of data was resolved through discussion with the senior author (SC). This process led to the iterative refinements of the data extraction table allowing us to capture important distinctions between papers relevant to our research questions. For instance, we refined our mapping of papers to HHC decisions to specify whether papers focused on and proposed a quantitative model for a given decision, considered that decision as a secondary outcome, made explicit assumptions about that decision as a model input, or simply made reference to that decision. Finally, the first reviewer revisited the completed data extraction table to ensure a consistent presentation and level of detail across all entries.

2.4. Analysis

For each paper, we identified the partial hierarchy of decisions in HHC considered. We then counted the number of papers that considered each unique hierarchy and produced a graphical summary of these data based on the graphical representation of the decision framework devised at section 2.1. For each decision, we then tabulated the OR approaches and accompanying solution methods used in the literature and, separately, the aspects of system performance considered.

2.4.1. Paper clustering

One of our aims was to identify whether there are groups of papers that, between them, provide a comprehensive and coherent basis for decision making across strategic, tactical and operational decisions. To do this, we adapted a clustering algorithm to find groups of papers that were coherent in terms of how system performance was conceived and then looked at how comprehensive the set of decisions addressed in each cluster was. To explore the coherence of papers in terms of the aspects of system performance considered, we computed a similarity score $s_{i,j} \in [0, 1]$ between all possible pairs of papers i and j:

$$s_{i,j} := \frac{|A_i \cap A_j|}{|A_i \cup A_j|}$$

with A_k denoting the set of aspects of system performance considered in paper k (the higher the overlap between papers i and j, the closer $s_{i,j}$ to 1). We then built an undirected, weighted graph with each node denoting a paper and an arc with weight $s_{i,j}$ existing between node i and node j if $s_{i,j} \geq 0.6$. We identified each connected component (i.e. set of nodes in the graph that are linked to each other by paths) in the obtained graph as a cluster of papers dealing with similar sets of aspects of system performance. Note that the lower the cut-off, the higher the average size of the connected components in the graph. We chose the cut-off (0.6) as the minimum real number such that at least two of the obtained clusters were formed of more than four papers.

3. Results

3.1. Decision framework

Figure 1 shows the set of decisions identified as important to the design and delivery of HHC services, spanning the strategic, tactical and operational planning levels. There is an implied hierarchy, or logical precedence relationship between some decisions, whereas others may be made in combination or in different sequences.

3.2. Literature search output

3.2.1. Summary of articles retrieved and data extracted

Our search identified 222 articles, with 4 review articles and 62 non-review articles meeting our inclusion criteria (Figure 2). Fifteen additional non-review articles identified in the 4 review articles were accepted. Table 1 shows the data extracted from the 77 non-review articles.

3.2.2. Decision hierarchies

Among the 59 of the 77 papers that addressed more than one decision, we identified 15 distinct partial hierarchies of decision (see Figure 3). The most commonly considered partial hierarchy (30 papers) was where staff rosters and home health care plans

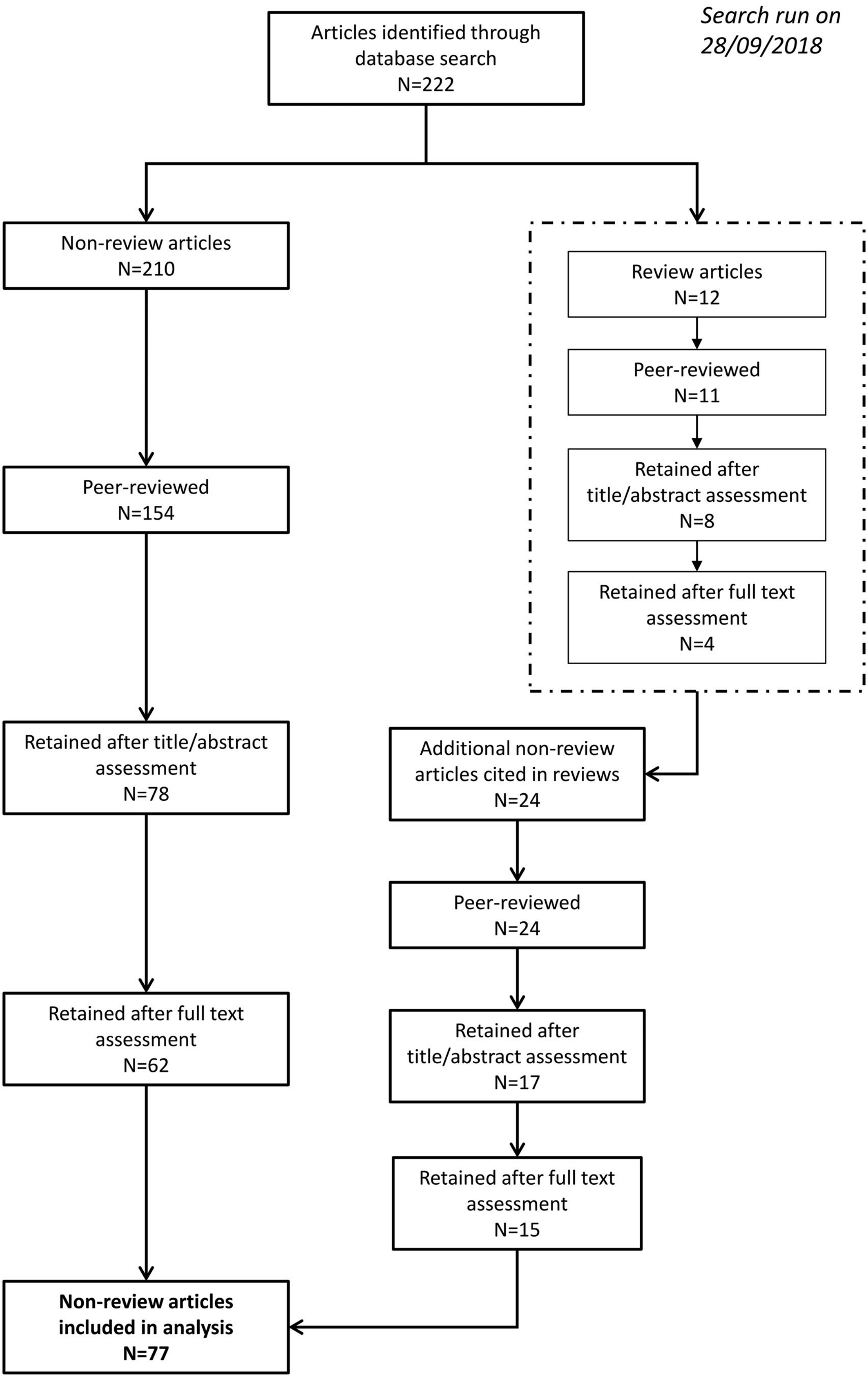

Figure 2. Literature search flow diagram, showing the number (N) of articles identified, meeting the inclusion criteria of peer-review, and retained for analysis after title/abstract assessment and after full-text reading. The left-hand side of the diagram shows the flow for non-review articles, whilst the right-hand side shows our process for identifying additional research papers from accepted review articles (which were then subject to the same sequence of inclusion criteria). We only extracted data from non-review article publication types.

Table 1. Data extracted from the non-review article publications that met the selection criteria.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Akjiratikarl et al. (2007)	Novel application of particle swarming optimisation to the home care scheduling problem.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Integer programming	Meta-heuristic approach based on Particle Swarm Optimisation	• Patient preferences (Deviation from preferred visit time) • Scheduler productivity (Planning time) • Staff travelling (Travelling time) • Staff utilisation (Travelling time)	Instances obtained from organisations
An et al. (2012)	Mixed-integer programming formulation and solution approach for the problem of scheduling visits for a nurse over a time horizon to fullfil the needs of a set of already assigned patients.	• Visit scheduling • Routing of visits	Multi-period (days)	Mixed-integer programming	Two-phase heuristic algorithm: i) determine a partial schedule for patients with shorter care intervals; ii) add remaining patients to obtain a complete schedule	• Scheduler productivity (Planning time) • Staff travelling (Travelling time)	Synthetic instances with realistic features
Argiento et al. (2016)	Bayesian framework to represent patients' home care demand evolution with time and to predict demand in future periods.	NA	Multi-period (weeks)	General linear mixed model with parameter estimation through Markov Chain Monte Carlo simulation	Markov Chain Monte Carlo simulation	• Continuity of care (*No stated metrics of performance*) • Staff utilisation (*No stated metrics of performance*)	Synthetic instances with realistic features
Bachouch et al. (2011)	Integer programming formulation for the rostering, scheduling, allocation and routing problems in health care.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Integer programming	Not specified - commercially available solver (LINGO and CPLEX) used	• Continuity of care (Staff per patient) • Scheduler productivity (Planning time) • Staff travelling (Travelling time)	None
Bard et al. (2013)	Development and comparison of a set of integer programming models and heuristic methods to allocate and route therapists to visits on a weekly basis.	• Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	The first two models were easily solved using commercial solvers (CPLEX). For the third model, two heuristic algorithms were developed that determine feasible solutions starting from lower bounds computed by solving relaxed versions of the original problem.	• Costs of staff time spent with patient (Treatment costs) • Number of teams (Number of home bases) • Staff travelling (Travelling costs) • Team size (Number of staff in a team)	Instances obtained from organisations
Bard, Shao and Jarrah (2014)	Heuristic algorithm for the problem of constructing weekly tours for home care therapists.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	Heuristic approach based on a greedy randomised adaptive search procedure	• Costs of staff time spent with patient (Treatment costs) • Scheduler productivity (Planning time) • Staff productivity (Ratio between treatment cost and total cost) • Staff travelling (Travelling costs)	Instances obtained from organisations
Bard, Shao, Qi, et al. (2014)	Mixed-integer programming formulation and two solution algorithms for the problem of constructing weekly tours for home care therapists.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	• Branch-cut-and-price approach • Heuristic algorithm based on rolling horizon method	• Costs of staff time spent with patient (Treatment costs) • Scheduler productivity (Planning time) • Staff productivity (*No stated metrics of performance*) • Staff travelling (Travelling costs)	Instances obtained from organisations

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Begur et al. (1997)	Development of a decision support system for scheduling and routing nurses at a home health care provider embedding a database management system, a heuristic algorithm and GIS technology.	• Allocation of staff • Routing of visits • Short-term fixes	Single-period (day)	Mixed-integer programming	Clarke and Wright's savings algorithm for staff-visit allocation + Rosenkrants, Sterns and Lewis's algorithm for route refinement of local travelling salesman sub-problems	• Scheduler productivity (Planning time) • Staff productivity (Travelling time)	Actual collaboration with organisations with implementation efforts
Bennett and Erera (2011)	Two heuristic approaches to solve the dynamic periodic fixed appointment time scheduling and routing problem.	• Visit scheduling • Routing of visits	Multi-period (weeks)	Combinatorial optimisation	Greedy heuristic approaches: • distance-based insertion criterion • capacity-based insertion criterion	• Scheduler productivity (Planning time) • Staff productivity (Number of visits) • Staff travelling (Travelling time per visit)	None
Benzarti et al. (2013)	Two mixed-integer programming formulations for the districting problem in home health care	• Districting	Single-period (several years)	Mixed-integer programming	Not specified - commercially available solver (CPLEX) used	• Continuity of care (*No stated metrics of performance*) • District compactness (Intra-district distances) • Staff travelling (Intra-district distances) • Team size (*No stated metrics of performance*) • Workload balance (Deviation from average workload)	None
Bertels and Fahle (2006)	Mixed-integer programming formulation and solution method combining the rostering and routing problems in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Mathematical programming formulation solved using a combination of constraint programming, tabu search and simulated annealing.	Combination of constraint programming, tabu search and simulated annealing	• Match of staff skills to patient needs (Mismatch between allocated staff skills and required skills) • Patient preferences (Deviation from preferred visit time) • Scheduler productivity (Planning time) • Staff preferences (Deviation from planned shift) • Staff travelling (Travelling time)	None
Blais et al. (2003)	Non-linear programming model to re-partition a territory from 4 to 6 districts in order to alleviate difficulties in managing nursing teams.	• Districting	Single-period (several years)	Non-linear programming (apparently based on a set covering formulation, though constraints are not explicitly reported)	Tabu search heuristic developed by Bozkaya et al. for political districting	• Scheduler productivity (Planning time) • Staff travelling (Travelling time) • Workload balance (Deviation from average workload)	Actual collaboration with organisations with implementation efforts
Bowers et al. (2015)	Solution algorithm for the problems of scheduling, allocation and routing over a time horizon, applied to midwifery.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Combinatorial optimisation	Modified Clarke-Wright algorithm including a component in the "savings" to reflect the benefit of the chosen staff matching patient's preferences	• Continuity of care (Deviation from preferred staff, Number of handovers) • Patient preferences (Deviation from preferred staff) • Staff travelling (Travelling time)	None

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Braekers et al. (2016)	Bi-objective mixed-integer programming formulation and solution method for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Mixed-integer programming	Meta-heuristic algorithm based on the multi-directional local search framework, with large neighbourhood search as a sub-heuristic	• Overtime (Overtime costs) • Patient preferences (Deviation from preferred staff, Deviation from preferred visit time) • Staff travelling (Travelling costs)	None
Cappanera and Scutellà (2015)	Integer linear programming formulations and heuristic procedure to jointly address the scheduling, allocation and routing problems in home care.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Integer linear programming	Branch and bound (using CPLEX)	• Scheduler productivity (Planning time) • Staff travelling (Maximum staff utilisation rate) • Workload balance (Minimum staff utilisation rate)	Synthetic instances with realistic features
Cappanera et al. (2018)	Cardinality-constrained approach to address the scheduling, allocation and routing problems in home health care, with patient demand subject to uncertainty.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Cardinality-constraint robust approach	Metaheuristic approach	• Continuity of care (Staff per patient) • Scheduler productivity (Planning time) • Workload balance (Maximum staff utilisation rate)	Synthetic instances with realistic features
Carello and Lanzarone (2014)	Cardinality-constrained approach to address the problem of allocation of staff to patients in home health care, with patient demand subject to uncertainty.	• Allocation of staff	Multi-period (weeks)	Cardinality-constrained approach (robust optimisation)	Not specified - commercially available solver (CPLEX) used	• Continuity of care (Reallocation costs) • Overtime (Overtime costs)	Instances obtained from organisations
Carello et al. (2018)	Cardinality-constrained approach to address the problem of allocating staff to patients in home health care, with patient demand subject to uncertainty and accounting for perspectives of different stakeholders.	• Allocation of staff	Multi-period (weeks)	Integer linear programming	Commercial solver (CPLEX)	• Continuity of care (Staff switches per patient) • Overtime (Overtime costs) • Scheduler productivity (Planning time) • Workload balance (Maximum staff utilisation rate)	Synthetic instances with realistic features
Cattafi et al. (2015)	Constraint programming formulation and heuristic approach for the problems of scheduling and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Constraint programming	Heuristic approach based on large neighbourhood search	• Continuity of care (Staff per patient) • Scheduler productivity (Planning time) • Staff travelling (Travelling time) • Workload balance (Staff workload)	Instances obtained from organisations
De Angelis (1998)	Stochastic programming model to determine the best resource allocation to home care for AIDS patients, within a limited budget and providing a minimum standard of service.	• Commissioning • Screening	Multi-period (weeks)	Markov chain and stochastic linear programming	Not mentioned - however, it seems that the linear approximation used makes the stochastic problem easy to solve	• Budget sufficiency (Number of accepted patients) • Staff utilisation (Number of accepted patients)	Synthetic instances with realistic features
Decerle et al. (2016)	Mixed-integer programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits • Coordination with other home care services	Single-period (day)	Mixed-integer programming	Two-phase meta-heuristic approach	• Costs of staff time spent with patient (Treatment costs) • Scheduler productivity (Planning time) • Staff travelling (Travelling costs)	None

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Decerle et al. (2018)	Mixed-integer programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits • Coordination with other home care services	Single-period (day)	Mixed-integer programming	Memetic algorithm	• Patient preferences (Deviation from preferred visit time) • Staff travelling (Travelling costs) • Synchronisation of visits (Penalty for non-respected synchronisation of visits)	Synthetic instances with realistic features
Du et al. (2017)	Integer programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Integer linear programming	Genetic algorithm with local search	• Costs of staff time spent with patient (Treatment costs) • Patient preferences (Deviation from preferred visit time) • Staff travelling (Travelling costs)	None
En-Nahli et al. (2015)	Multi-objective mixed-integer programming formulation for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Multi-objective optimisation (mixed-integer programming)	Not specified - commercially available solver (CPLEX) used	• Patient preferences (Deviation from preferred staff) • Staff preferences (Minimum staff utilisation rate, Staff waiting time) • Staff travelling (Travelling time)	None
Erdem and Bulkan (2017)	Two-stage heuristic solution approach for large-scale instances of the problem of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Mixed-integer programming	Two-stage algorithm: i) clustering of nurses and jobs; ii) generation of scheduling/ routing using a variable neighbourhood search algorithm	• Demand satisfaction (Penalty for unassigned visits) • Overtime (Overtime costs) • Staff preferences (Deviation from preferred visit time) • Staff travelling (Travelling costs)	None
Errarhout et al. (2016)	Two-stage stochastic programming approach for the problem of allocating nurses to patients over a time horizon in home health care.	• Allocation of staff	Multi-period (weeks)	Stochastic, mixed-integer programming	Not specified - commercially available solver (CPLEX) used	• Staff travelling (Travelling distance) • Workload balance (Workload variability)	None
Eveborn et al. (2006)	Decision support system aimed at reducing the time spent planning daily visits by home health care organisations as well as at improving service efficiency.	• Visit scheduling • Allocation of staff • Routing of visits • Short-term fixes	Multi-period (days)	Integer programming (based on set partitioning model)	Repeated matching (combination of optimisation methods and heuristics)	• Continuity of care (Deviation from staff working area, Staff per patient) • Match of staff skills to patient needs (Mismatch between allocated staff skills and required skills) • Patient preferences (Deviation from preferred staff, Deviation from preferred visit time) • Scheduler productivity (Planning time) • Staff preferences (Deviation from planned shift) • Staff travelling (Travelling costs, Travelling time)	Actual collaboration with organisations with implementation efforts

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Eveborn et al. (2009)	Decision support system aimed at reducing the time spent planning daily visits by home health care organisations as well as at improving service efficiency.	• Visit scheduling • Allocation of staff • Routing of visits • Short-term fixes	Multi-period (days)	Integer programming (based on set partitioning model)	Repeated matching (combination of optimisation methods and heuristics)	• Continuity of care (Deviation from staff working area, Staff per patient) • Match of staff skills to patient needs (Mismatch between allocated staff skills and required skills) • Patient preferences (Deviation from preferred staff, Deviation from preferred visit time) • Scheduler productivity (Planning time) • Staff preferences (Deviation from planned shift) • Staff travelling (Travelling costs, Travelling time)	Actual collaboration with organisations with implementation efforts
Fikar and Hirsch (2015)	Integer programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Integer programming	Matheuristic approach based on tabu search and consisting of two stages: creation of walking routes and optimisation of the transport system	• Overtime (Deviation from planned shift)	Synthetic instances with realistic features
Fikar et al. (2016)	Discrete-event driven heuristic approach for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits • Short-term fixes	Single-period (day)	Integer programming	Discrete-event driven metaheuristic approach	• Scheduler productivity (Planning time) • Staff utilisation (Staff utilisation rate, Vehicle utilisation rate)	None
Guericke and Suhl (2017)	Mixed-integer programming formulation and heuristic algorithm for the problems of rostering, scheduling, allocation and routing in home health care.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	Meta-heuristic approach based on adaptive large neighbourhood search	• Staff utilisation (Penalty for unassigned visits, Penalty for unassigned weekend shifts, Staff waiting time, Travelling time)	None
Hertz and Lahrichi (2009)	Mixed-integer programming formulation and heuristic algorithm for the problem of allocating nurses to patients in home health care, with dynamic assignment based on current workload.	• Allocation of staff	Single-period (month)	Mixed-integer programming	Meta-heuristic approach based on Tabu search	• Workload balance (Deviation from average number of patients per staff)	None
Hewitt et al. (2016)	Using an existing integer programming formulation for the problems of rostering, scheduling, allocation and routing in home health care in order to compare different planning horizons.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	Heuristic approach based on the "record-to-record travel algorithm"	• Continuity of care (Staff per patient) • Staff travelling (Travelling time)	None

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Hiermann et al. (2015)	Generic framework for the problems of scheduling, allocation and routing in home health care that can be easily adapted to include different requirements.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Two-stage approach based on constraint programming and metaheuristics	• Initial solution determined through constraint programming or random construction • Solution improvement through a metaheuristic algorithm: variable neighbourhood search, memetic algorithm, scatter search, simulated annealing	• Demand satisfaction (Penalty for unassigned visits) • Overtime (Deviation from planned shift) • Patient preferences (Deviation from preferred staff, Deviation from preferred visit time) • Scheduler productivity (Planning time) • Staff preferences (Deviation from planned shift, Deviation from preferred patient, Travelling time) • Staff travelling (Travelling time)	Synthetic instances with realistic features
Hindle et al. (2000)	Estimating yearly travelling distance for home health care to inform fund allocation.	NA	Single-period (year)	Multiplicative analytical model	NA	• Demand satisfaction (Travelling distance, Travelling time)	Actual collaboration with organisations with implementation efforts
Hindle et al. (2009)	Estimating yearly travelling distance for home health care to inform fund allocation.	NA	Single-period (year)	Simplified Modelling of Spatial Systems, consisting of using simple mathematical functions to approximate travelling distances and times to degrees of accuracy comparable to those achieved by more complex routing algorithms	NA	• Demand satisfaction (Travelling distance, Travelling time)	Instances obtained from organisations
Koeleman et al. (2012)	Markov decision process to derive optimal patient admission policies and workforce size in home care.	• Screening • Team size and composition	Single-period (several weeks)	Markov decision process	• Analytical solution of the model • Heuristic approach ("trunk reservation")	• Demand satisfaction (Cost of accepting patients, Cost of delaying patients, Cost of rejecting patients)	None
Lanzarone et al. (2010)	Markov chains to support resource planning in home care by estimating workload over a time horizon.	NA	Multi-period (weeks)	Stochastic modelling (Markov chain) + statistical data analysis (not specified)	NA	• Continuity of care (*No stated metrics of performance*) • Workload balance (*No stated metrics of performance*)	Actual collaboration with organisations with implementation efforts
Lanzarone and Matta (2012)	Stochastic programming approach for allocating patients to operators in home care.	• Allocation of staff	Single-period (several weeks)	Stochastic modelling	Analytical derivation of the best assignment policy	• Continuity of care (Staff per patient) • Workload balance (Deviation from planned shift)	Synthetic instances with realistic features
		• Allocation of staff			Not specified - OPL 5.1 solver used		

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Lanzarone et al. (2012)	Set of mathematical programming formulations for different variants of the problem of allocating patients to operators in home care		Multi-period (weeks)	(Stochastic) integer programming		• Continuity of care (Staff per patient) • Workload balance (Minimum staff utilisation rate)	Actual collaboration with organisations with implementation efforts
Lin et al. (2016)	Mixed-integer programming formulation for the problem of assigning therapists to patients over a time horizon in home health care.	• Allocation of staff	Multi-period (days)	Mixed-integer programming	Not specified - commercially available solver (Gurobi Optimizer) used	• Demand satisfaction (Number of allocated patients)	Synthetic instances with realistic features
Lin et al. (2017)	Mixed-integer programming formulation and heuristic algorithm for the districting problem in the context of the "meals-on-wheels" service.	• Districting	Single-period (day)	Mixed-integer programming	Heuristic method based on a greedy approach	• Number of teams (Number of districts) • Scheduler productivity (Planning time)	None
Lin et al. (2018)	Mixed-integer programming formulation and heuristic algorithm for the problems of rostering, scheduling, allocation, routing and re-rostering in home health care.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits • Short-term fixes	Multi-period (days)	Mixed-integer programming	Meta-heuristic approach based on harmony search	• Disruptions to planned work (Deviation from original visit schedule) • Overtime (Overtime costs) • Staff travelling (Travelling costs)	None
Liu et al. (2013)	Mixed-integer programming formulation, tabu search algorithm and genetic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Mixed-integer programming	• Tabu search heuristic • Genetic algorithm	• Staff travelling (Travelling costs)	None
Liu et al. (2014)	Tabu search algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	Tabu search heuristic	• Staff travelling (Travelling distance)	None
Liu et al. (2017)	Branch and price algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Integer linear programming	Branch-and-price algorithm	• Demand satisfaction (Penalty for unassigned visits) • Scheduler productivity (Planning time) • Staff travelling (Travelling costs)	None
Liu et al. (2018)	Bi-objective mixed-integer programming approach for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Bi-objective mixed-integer programming	Metaheuristic approach	• Costs of staff time spent with patient (Treatment costs) • Patient preferences (Additional treatment time) • Staff travelling (Travelling costs)	None
López-Santana et al. (2016)	Multi-agent approach for the problems of scheduling, allocation and routing in home health care, enabling dynamic handling of new requests.	• Visit scheduling • Allocation of staff • Routing of visits • Short-term fixes	Multi-period (day fractions)	Multi-agent approach, a step of which consists of a mixed-integer programming problem	JADE (Java Agent Development Framework), with MIP problem solved using commercial optimisation software	• Demand satisfaction (Amount of skills allocated to patients) • Staff travelling (Travelling time)	None

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Manerba and Mansini (2016)	Branch-and-cut approach to solve the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Integer programming	Branch-and-price algorithm	• Match of staff skills to patient needs (Suitability score of patient-staff allocation)	None
Mankowska et al. (2014)	Mixed-integer programming formulation and heuristic algorithms for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits • Coordination with other home care services	Single-period (day)	Mixed-integer programming	The authors present several heuristic approaches that can deal with the complexity of the problem	• Patient preferences (Deviation from preferred visit time) • Punctuality (Tardiness) • Staff travelling (Travelling distance)	None
Marcon et al. (2017)	Multi-agent simulation model for dynamically solving the routing problem in home health care, given a pre-existing scheduling, allocation and routing solution.	• Short-term fixes	Single-period (day)	Multi-agent modelling	Multi-agent simulation	• Staff autonomy (*No stated metrics of performance*) • Staff travelling (Travelling time)	None
Maya Duque et al. (2015)	Bi-objective integer programming formulation and heuristic approach for the problems of scheduling, allocation and routing, presented as the core optimisation component of a decision support system developed to the benefit of a home care organisation.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Bi-objective optimisation (integer programming), with formulation based on set partitioning	Three-stage process of identifying set of possible schedules for a patient, set partitioning to allocate staff to patient schedules, then randomised local search to reduce travel time within permit margin on preference meeting	• Patient preferences (Deviation from preferred visit time, Suitability score of patient-staff allocation) • Scheduler productivity (Planning time) • Staff preferences (Deviation from preferred visit time, Suitability score of patient-staff allocation) • Staff travelling (Travelling distance)	Actual collaboration with organisations with implementation efforts
Mutingi and Mbohwa (2013)	Genetic algorithm applied to routing of visits in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Combinatorial optimisation	Group genetic algorithm	• Patient preferences (Deviation from preferred visit time) • Scheduler productivity (Planning time) • Staff travelling (Travelling distance) • Staff utilisation (*No stated metrics of performance*)	None
Mutingi and Mbohwa (2014)	Fuzzy-based particle swarm optimisation approach for the problem of assigning staff to visits in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Integer programming	Fuzzy-based particle swarm optimisation algorithm	• Patient preferences (Deviation from preferred visit time) • Scheduler productivity (Planning time) • Workload balance (Deviation from average visits per staff)	None
Nasir and Dang (2016)	Mixed-integer programming formulation for the problems of scheduling, allocation and routing in home health care and method to predict whether a patient will be scheduled or not based on their distance to the health care centre or the width of their time window.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Mixed-integer programming	Not specified - commercially available solver (CPLEX) used	• Patient preferences (Deviation from preferred visit time) • Staff travelling (Travelling costs)	None

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Nasir and Dang (2018)	Mixed-integer programming formulation and heuristic algorithm to jointly address the problems of patient selection, nurse hiring, rostering, scheduling, allocation and routing in home health care.	• Team size and composition • Screening • Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	Meta-heuristic approach based on variable neighbourhood search	• Demand satisfaction (Cost of delaying patients) • Staff costs (Wage costs) • Staff travelling (Travelling distance) • Workload balance (Deviation from average staff idle time, Workload variability)	None
Nasir et al. (2018)	Integer programming formulation for the problem of determining the optimal number of staff to deploy and offices to open over a given time window, with the aim to enable coordination between home health care and telehealth services.	• Team size and composition • Visit scheduling • Allocation of staff • Coordination with other home care services	Single-period (day)	Integer linear programming	Commercial solver (CPLEX)	• Match of staff skills to patient needs (Penalty for allocating staff without experience of that patient type) • Patient preferences (Score of similarity of patients belonging to the same cluster) • Staff costs (Wage costs) • Staff travelling (Travelling costs)	None
Nickel et al. (2012)	Constraint programming formulations and heuristic approaches for the problems of rostering, scheduling, allocation and routing in home health care.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits • Short-term fixes	Multi-period (days)	Constraint programming	Constraint programming techniquest + heuristics on adaptive large neighbourhood search and tabu search	• Continuity of care (Staff per patient) • Demand satisfaction (Penalty for unassigned visits) • Disruptions to planned work (Deviation from original visit schedule) • Overtime (Deviation from planned shift) • Staff travelling (Travelling distance)	Synthetic instances with realistic features
Quintana et al. (2017)	Clustering technique for solving very large instances of the problems of scheduling, allocation and routing in home care, with the aim to find the best trade-off between the number of caregivers deployed and the amount of unproductive time.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Clustering	Heuristic method based on a greedy approach	• Staff productivity (Number of staff deployed) • Staff utilisation (Unproductive time)	Instances obtained from organisations
Rasmussen et al. (2012)	Set partitioning formulation and branch and price algorithm for the problems of scheduling, allocation and routing in home care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Integer programming	Branch-and-price algorithm, coupled with a procedure of visit clustering	• Demand satisfaction (Penalty for unassigned visits) • Patient preferences (Deviation from preferred patient) • Staff travelling (Travelling costs)	Synthetic instances with realistic features
Redjem and Marcon (2016)	Heuristic algorithm for the problems of scheduling and routing in home care.	• Visit scheduling • Routing of visits	Single-period (day)	Mixed-integer programming	Heuristic approach named "Caregivers Routing Heuristic"	• Scheduler productivity (Planning time) • Staff productivity (Unproductive time)	Instances obtained from organisations

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Rest and Hirsch (2015)	Mixed-integer programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Mixed-integer programming	Meta-heuristic approach based on tabu search	• Match of staff skills to patient needs (Mismatch between allocated staff skills and required skills) • Punctuality (Tardiness) • Staff preferences (Deviation from planned shift) • Staff travelling (Travelling distance)	Synthetic instances with realistic features
Rest and Hirsch (2016)	Mixed-integer programming formulation and heuristic algorithm for the problems of rostering, scheduling, allocation and routing in home health care.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits • Short-term fixes	Single-period (day)	Mixed-integer programming	Combination of dynamic programming (solving the shortest path problem between locations at different times of the day) and meta-heuristics based on tabu search	• Match of staff skills to patient needs (Mismatch between allocated staff skills and required skills) • Punctuality (Tardiness) • Staff preferences (Deviation from planned shift) • Staff travelling (Travelling time)	Synthetic instances with realistic features
Rodriguez et al. (2015)	Stochastic programming approach for the problem of staff dimensioning over a time horizon in home health care.	• Team size and composition	Single-period (several months)	Two-stage, integer linear programming	Branch-and-cut algorithm	• Staff costs (Wage costs)	None
Shao et al. (2012)	Mixed-integer programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	Greedy randomised adaptive search procedure	• Costs of staff time spent with patient (Treatment costs) • Overtime (Overtime costs) • Staff productivity (Ratio between treatment cost and total cost) • Staff travelling (Travelling costs)	Synthetic instances with realistic features
Shi et al. (2017a)	Mixed-integer programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care, with uncertainty in capacity constraints modelled using fuzzy credibility theory.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Mixed-integer programming	Hybrid genetic algorithm, with stochastic simulation to evaluate candidate solutions	• Staff travelling (Travelling distance)	None
Shi et al. (2017b)	Stochastic programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Stochastic programming	Hybrid genetic algorithm	• Patient preferences (Deviation from preferred visit time) • Staff preferences (Overtime costs) • Staff travelling (Travelling costs)	None
Shi et al. (2018)	Stochastic programming formulation and heuristic algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Stochastic programming	Heuristic algorithm based on simulated annealing	• Patient preferences (Deviation from preferred visit time) • Staff preferences (Overtime costs) • Staff travelling (Travelling costs)	None

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Trautsamwieser et al. (2011)	Integer programming formulation and heuristic algorithm for the problems of rostering, scheduling, allocation and routing in home health care, with sensitivity analysis carried out on parameters regarding travelling times in order to account for delays due to flood disasters.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Integer programming	Meta-heuristic approach based on variable neighbourhood search	• Patient preferences (Deviation from preferred staff, Suitability score of patient-staff allocation) • Scheduler productivity (Planning time) • Staff preferences (Overtime costs, Staff waiting time) • Staff travelling (Travelling time)	Instances obtained from organisations
Trautsamwieser and Hirsch (2011)	Integer programming formulation and heuristic algorithm for the problems of rostering, scheduling, allocation and routing in home health care.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Integer programming	Metaheuristic approach based on variable neighbourhood search	• Patient preferences (Deviation from preferred visit time, Suitability score of patient-staff allocation) • Scheduler productivity (Planning time) • Staff preferences (Deviation from planned shift, Unpaid driving time) • Staff travelling (Travelling time)	Instances obtained from organisations
Trautsamwieser and Hirsch (2014)	Mixed-integer programming formulation and branch price and cut approach for the problems of rostering, scheduling, allocation and routing in home health care.	• Staff rostering • Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Mixed-integer programming	Branch-price-and-cut algorithm	• Overtime (Deviation from planned shift) • Scheduler productivity (Planning time)	Synthetic instances with realistic features
Wirnitzer et al. (2016)	Mixed-integer programming formulation for the problems of rostering and allocation in home health care.	• Staff rostering • Allocation of staff	Multi-period (days)	Mixed-integer programming	Not specified - commercially available solver (Gurobi) used	• Continuity of care (Staff per patient, Staff per tour, Staff switches per patient) • Scheduler productivity (Planning time)	Instances obtained from organisations
Yalçındağ et al. (2016)	Integer linear programming formulation and heuristic procedure for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Multi-period (days)	Integer linear programming	Not specified - commercially available solver (CPLEX) used	• Scheduler productivity (Planning time) • Staff travelling (Travelling time) • Workload balance (Maximum staff utilisation rate, Minimum staff utilisation rate)	Synthetic instances with realistic features
Yuan et al. (2015)	Stochastic programming formulation and branch and price algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Stochastic programming	Branch-and-price algorithm	• Costs of staff time spent with patient (Treatment costs) • Punctuality (Tardiness) • Staff costs (Wage costs) • Staff travelling (Travelling costs)	None
Yuan and Jiang (2017)	Integer programming formulation and heuristic algorithm for the problem of minimising disruption from planned daily schedules in home health care.	• Short-term fixes	Single-period (day)	Integer programming	Meta-heuristic approach based on tabu search	• Disruptions to planned work (Deviation from original visit schedule) • Scheduler productivity (Planning time)	Synthetic instances with realistic features

(*continued*)

Table 1. Continued.

ID	Aim of the study	Decisions modelled	Planning horizon	Modelling approach	Solution approach	Aspects of performance (metrics of performance)	Level of engagement with current practice
Yuan et al. (2018)	Stochastic programming formulation and branch and price algorithm for the problems of scheduling, allocation and routing in home health care.	• Visit scheduling • Allocation of staff • Routing of visits	Single-period (day)	Stochastic programming	Branch and Price approach, with expected failure cost obtained using a discrete approximation method	• Demand satisfaction (Penalty for unassigned visits) • Scheduler productivity (Planning time) • Staff travelling (Travelling costs)	None
Zhang et al. (2015)	Integer programming formulations to support decisions about strategies of resource allocation to patients in long-term home care.	• Screening	Multi-period (years)	Integer programming	• Optimal solution found via Microsoft Solver Foundation (algorithm not specified) • Heuristic solutions computed as admission policies: FIFO, shortest processing time, spread admissions across patient groups	• Punctuality (Maximum tardiness, Tardiness)	Instances obtained from organisations

are taken as input and the allocation of staff to patients, appointment schedules and the routing of staff are decided in combination.

3.2.3. Or approaches in HHC

Table 2 shows the OR approaches and solution methods adopted to address each of the decision problems in HHC. We summarise our findings below.

All studies of **districting** use mixed-integer programming. Two aspects of system performance are addressed either using different models, each with one aspect as the objective and the other as a hard constraint (Benzarti et al., 2013), or by minimising a weighted sum of two components (Blais et al., 2003). Lin et al. (2017) develop a greedy algorithm to rapidly obtain near-optimal solutions, whereas the other studies apply existing algorithms and focus on their applicability in the real world.

Mathematical programming approaches (integer, mixed/integer, stochastic) are also applied in 3 of the 4 studies about **team size and composition** (Rodriguez et al., 2015; Nasir & Dang, 2018; Nasir et al., 2018). In the other paper, Koeleman et al. (2012) calculate the impact on workforce size of a Markov decision process framed to give optimal patient admission (screening) policies given the demand for service.

In other papers addressing this decision of patient **screening**, Zhang et al. (2015) and Nasir and Dang (2018) use mixed-integer programming and constraint programming, respectively, proposing meta-heuristic algorithms to deal with the computational complexity of the problem. De Angelis (1998) jointly models the **commissioning** and **screening** decisions using a linearly approximated stochastic programming model, with resource needs for different types of patients estimated using an existing stochastic model and resource limits (budget) included as constraints. The objective is to maximise the weekly number of AIDS patients admitted to home care, with an implicit assumption that this would lead to the best allocation of resources.

The vast majority of the studies addressing **staff rostering, visit scheduling, allocation of staff and routing visits** propose mixed-integer programming formulations based on the vehicle routing problem and incorporating one or more additional features (e.g. time windows, activity interdependencies, workload balance). The high computational cost associated with such formulations is usually tackled by developing heuristic algorithms able to produce good solutions in a reasonable amount of time. Less common approaches include robust optimisation (Carello & Lanzarone, 2014), stochastic programming (Yuan et al., 2015; Lanzarone & Matta, 2012; Lanzarone et al., 2012; Errarhout et al., 2016), multi-objective optimisation (Maya Duque et al., 2015; En-

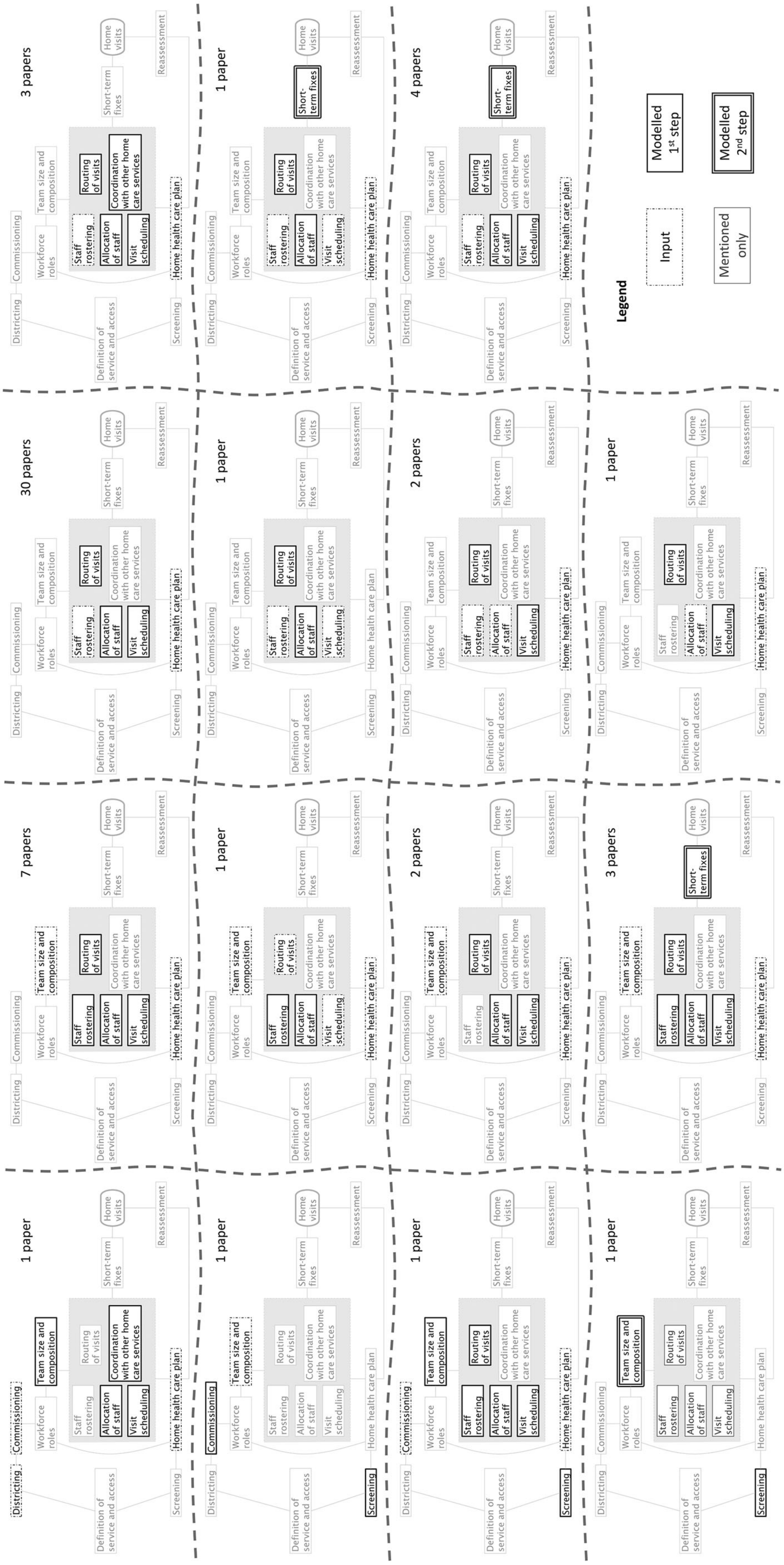

Figure 3. The set of partial decision hierarchies of decision among the 59 of 77 reviewed papers that considered more than one of the identified decision problems in home health care. Each tile shows a different subset of decisions, with the number of papers considering precisely that combination of decisions given at the top right of the tile. The line-style used for the boxes denotes whether, within those papers, the respective decisions are: merely mentioned as relevant; viewed as a necessary prior step but not modelled; modelled at the first (or only) step of analysis; or modelled at a second step of analysis.

Table 2. OR approaches by decision.

Decision (number of papers)	OR approach (number of papers)	Solution method (reference)
Definition of service and access (n = 0)	(n = 0)	–
Districting (n = 3)	• (Mixed-)integer programming (n = 2) • Non-linear programming (n = 1)	• Other heuristic algorithm (Lin et al., 2017) • Not specified - commercially available software (Benzarti et al., 2013) • Tabu search (Blais et al., 2003)
Screening (n = 4)	• Markov chain and stochastic programming (n = 1) • Markov decision process (n = 1) • (Mixed-)integer programming (n = 2)	• Not specified - commercially available software (De Angelis, 1998) • Trunk reservation algorithm (Koeleman et al., 2012) • Variable neighbourhood search (Nasir & Dang, 2018) • Other heuristic algorithm (Zhang et al., 2015) • Not specified - commercially available software (Zhang et al., 2015)
Commissioning (n = 1)	• Markov chain and stochastic programming (n = 1)	• Not specified - commercially available software (De Angelis, 1998)
Workforce roles (n = 0)	(n = 0)	–
Team size and composition (n = 4)	• Markov decision process (n = 1) • (Mixed-)integer programming (n = 3)	• Trunk reservation algorithm (Koeleman et al., 2012) • Variable neighbourhood search (Nasir & Dang, 2018) • Branch and cut (Rodriguez et al., 2015) • Not specified - commercially available software (Nasir et al., 2018)
Home health care plan (n = 0)	(n = 0)	–
Staff rostering (n = 12)	• (Mixed-)integer programming (n = 11)	• Greedy randomised adaptive search procedure (Bard, Shao & Jarrah, 2014) • Adaptive large neighbourhood search (Guericke & Suhl, 2017) • Record-to-record travel algorithm (Hewitt et al., 2016) • Harmony search (Lin et al., 2018) • Variable neighbourhood search (Trautsamwieser et al., 2011; Trautsamwieser & Hirsch, 2011; Nasir & Dang, 2018) • Combination of dynamic programming and tabu search (Rest & Hirsch, 2016) • Branch price and cut (Trautsamwieser & Hirsch, 2014) • Not specified - commercially available software (Bachouch et al., 2011; Wirnitzer et al., 2016)
	• Constraint programming (n = 1)	• Combination of tabu search and adaptive large neighbourhood search (Nickel et al., 2012)
Allocation of staff (n = 61)	• (Mixed-)integer programming (n = 46)	• Savings algorithm and insertion heuristics (Begur et al., 1997) • Savings algorithm (Bowers et al., 2015) • Particle swarm optimisation algorithm (Akjiratikarl et al., 2007) • Greedy randomised adaptive search procedure (Shao et al., 2012; Bard, Shao & Jarrah, 2014) • Branch price and cut (Bard, Shao, Qi, et al., 2014; Trautsamwieser & Hirsch, 2014) • Large neighbourhood search (Braekers et al., 2016) • Adaptive large neighbourhood search (Guericke & Suhl, 2017) • Branch and bound (Cappanera & Scutellà, 2015) • Memetic algorithm (Decerle et al., 2018) • Genetic algorithm (Liu et al., 2013; Mutingi & Mbohwa, 2013; Du et al., 2017; Shi et al., 2017a) • Combination of clustering and variable neighbourhood search (Erdem & Bulkan, 2017) • Repeated matching (Eveborn et al., 2006; Eveborn et al., 2009) • Tabu search (Hertz & Lahrichi, 2009; Liu et al., 2013; Liu et al., 2014; Fikar & Hirsch, 2015; Rest & Hirsch, 2015) • Discrete event driven metaheuristics (Fikar et al., 2016) • Record-to-record travel algorithm (Hewitt et al., 2016) • Harmony search (Lin et al., 2018) • Branch and price (Rasmussen et al., 2012; Manerba & Mansini, 2016; Liu et al., 2017) • Fuzzy-based particle swarm optimisation algorithm (Mutingi & Mbohwa, 2014) • Variable neighbourhood search (Trautsamwieser et al., 2011; Trautsamwieser & Hirsch, 2011; Nasir & Dang, 2018) • Combination of dynamic programming and tabu search (Rest & Hirsch, 2016) • Other heuristic algorithm (Bard et al., 2013; Bard, Shao, Qi, et al., 2014; Mankowska et al., 2014; Maya Duque et al., 2015; Decerle et al., 2016; Liu et al., 2018) • Not specified - commercially available software (Bachouch et al., 2011; Bard et al., 2013; En-Nahli et al., 2015; Lin et al., 2016; Carello et al., 2018; Nasir & Dang, 2016; Wirnitzer et al., 2016; Yalçındağ et al. 2016; Nasir et al., 2018)
	• Constraint programming (n = 4)	• Combination of tabu search and simulated annealing (Bertels & Fahle, 2006) • Large neighbourhood search (Cattafi et al., 2015) • Variable neighbourhood search (Hiermann et al., 2015) • Memetic algorithm (Hiermann et al., 2015) • Scatter search (Hiermann et al., 2015) • Simulated annealing (Hiermann et al., 2015)

(*continued*)

Table 2. Continued.

Decision (number of papers)	OR approach (number of papers)	Solution method (reference)
		• Combination of tabu search and adaptive large neighbourhood search (Nickel et al., 2012)
	• Stochastic programming (n = 7)	• Analytical derivation of optimal solution (Lanzarone & Matta, 2012) • Genetic algorithm (Shi et al., 2017b) • Simulated annealing (Shi et al., 2018) • Branch and price (Yuan et al., 2015; Yuan et al., 2018) • Not specified - commercially available software (Lanzarone et al., 2012; Errarhout et al., 2016)
	• Cardinality-constrained approach (n = 2)	• Other heuristic algorithm (Cappanera et al., 2018) • Not specified - commercially available software (Carello & Lanzarone, 2014)
	• Multi-agent modelling (n = 1)	• Multi-agent simulation (López-Santana et al., 2016)
	• Clustering (n = 1)	• Greedy algorithm (Quintana et al., 2017)
Visit scheduling (n = 54)	• (Mixed-)integer programming (n = 43)	• Insertion heuristics (Bennett & Erera, 2011) • Savings algorithm (Bowers et al., 2015) • Particle swarm optimisation algorithm (Akjiratikarl et al., 2007) • Greedy randomised adaptive search procedure (Shao et al., 2012; Bard, Shao & Jarrah, 2014) • Branch price and cut (Bard, Shao, Qi, et al. 2014; Trautsamwieser & Hirsch, 2014) • Large neighbourhood search (Braekers et al., 2016) • Adaptive large neighbourhood search (Guericke & Suhl, 2017) • Branch and bound (Cappanera & Scutellà, 2015) • Memetic algorithm (Decerle et al., 2018) • Genetic algorithm (Liu et al., 2013; Mutingi & Mbohwa, 2013; Du et al., 2017; Shi et al., 2017a) • Combination of clustering and variable neighbourhood search (Erdem & Bulkan, 2017) • Repeated matching (Eveborn et al., 2006; Eveborn et al., 2009) • Tabu search (Liu et al., 2013; Liu et al., 2014; Fikar & Hirsch, 2015; Rest & Hirsch, 2015) • Discrete event driven metaheuristics (Fikar et al., 2016) • Record-to-record travel algorithm (Hewitt et al., 2016) • Harmony search (Lin et al., 2018) • Branch and price (Rasmussen et al., 2012; Manerba & Mansini, 2016; Liu et al., 2017) • Fuzzy-based particle swarm optimisation algorithm (Mutingi & Mbohwa, 2014) • Variable neighbourhood search (Trautsamwieser et al., 2011; Trautsamwieser & Hirsch, 2011; Nasir & Dang, 2018) • Combination of dynamic programming and tabu search (Rest & Hirsch, 2016) • Other heuristic algorithm (An et al., 2012; Bard, Shao, Qi, et al., 2014; Mankowska et al., 2014; Maya Duque et al., 2015; Decerle et al., 2016; Redjem & Marcon, 2016; Liu et al., 2018) • Not specified - commercially available software (Bachouch et al., 2011; En-Nahli et al., 2015; Nasir & Dang, 2016; Yalçındağ et al. 2016; Nasir et al., 2018)
	• Constraint programming (n = 4)	• Combination of tabu search and simulated annealing (Bertels & Fahle, 2006) • Large neighbourhood search (Cattafi et al., 2015) • Variable neighbourhood search (Hiermann et al., 2015) • Memetic algorithm (Hiermann et al., 2015) • Scatter search (Hiermann et al., 2015) • Simulated annealing (Hiermann et al., 2015) • Combination of tabu search and adaptive large neighbourhood search (Nickel et al., 2012)
	• Cardinality-constrained approach (n = 1)	• Other heuristic algorithm (Cappanera et al., 2018)
	• Multi-agent modelling (n = 1)	• Multi-agent simulation (López-Santana et al., 2016)
	• Clustering (n = 1)	• Greedy algorithm (Quintana et al., 2017)
	• Stochastic programming (n = 4)	• Genetic algorithm (Shi et al., 2017b) • Simulated annealing (Shi et al., 2018) • Branch and price (Yuan et al., 2015; Yuan et al., 2018)
Routing of visits (n = 55)	• (Mixed-)integer programming (n = 44)	• Savings algorithm and insertion heuristics (Begur et al., 1997) • Insertion heuristics (Bennett & Erera, 2011) • Savings algorithm (Bowers et al., 2015) • Particle swarm optimisation algorithm (Akjiratikarl et al., 2007) • Greedy randomised adaptive search procedure (Shao et al., 2012; Bard, Shao & Jarrah, 2014) • Branch price and cut (Bard, Shao, Qi, et al., 2014; Trautsamwieser & Hirsch, 2014) • Large neighbourhood search (Braekers et al., 2016) • Adaptive large neighbourhood search (Guericke & Suhl, 2017) • Branch and bound (Cappanera & Scutellà, 2015) • Memetic algorithm (Decerle et al., 2018) • Genetic algorithm (Liu et al., 2013; Mutingi & Mbohwa, 2013; Du et al.,

(*continued*)

Table 2. Continued.

Decision (number of papers)	OR approach (number of papers)	Solution method (reference)
		2017; Shi et al., 2017a) • Combination of clustering and variable neighbourhood search (Erdem & Bulkan, 2017) • Repeated matching (Eveborn et al., 2006; Eveborn et al., 2009) • Tabu search (Liu et al., 2013; Liu et al., 2014; Fikar & Hirsch, 2015; Rest & Hirsch, 2015) • Discrete event driven metaheuristics (Fikar et al., 2016) • Record-to-record travel algorithm (Hewitt et al., 2016) • Harmony search (Lin et al., 2018) • Branch and price (Rasmussen et al., 2012; Manerba & Mansini, 2016; Liu et al., 2017) • Fuzzy-based particle swarm optimisation algorithm (Mutingi & Mbohwa, 2014) • Variable neighbourhood search (Trautsamwieser et al., 2011; Trautsamwieser & Hirsch, 2011; Nasir & Dang, 2018) • Combination of dynamic programming and tabu search (Rest & Hirsch, 2016) • Other heuristic algorithm (An et al., 2012; Bard et al., 2013; Bard, Shao, Qi, et al., 2014; Mankowska et al., 2014; Maya Duque et al., 2015; Decerle et al., 2016; Redjem & Marcon, 2016; Liu et al., 2018) • Not specified - commercially available software (Bachouch et al., 2011; Bard et al., 2013; En-Nahli et al., 2015; Nasir & Dang, 2016; Yalçındağ et al. 2016)
	• Constraint programming (n = 4)	• Combination of tabu search and simulated annealing (Bertels & Fahle, 2006) • Large neighbourhood search (Cattafi et al., 2015) • Variable neighbourhood search (Hiermann et al., 2015) • Memetic algorithm (Hiermann et al., 2015) • Scatter search (Hiermann et al., 2015) • Simulated annealing (Hiermann et al., 2015) • Combination of tabu search and adaptive large neighbourhood search (Nickel et al., 2012)
	• Cardinality-constrained approach (n = 1)	• Other heuristic algorithm (Cappanera et al., 2018)
	• Multi-agent modelling (n = 1)	• Multi-agent simulation (López-Santana et al., 2016)
	• Clustering (n = 1)	• Greedy algorithm (Quintana et al., 2017)
	• Stochastic programming (n = 4)	• Genetic algorithm (Shi et al., 2017b) • Simulated annealing (Shi et al., 2018) • Branch and price (Yuan et al., 2015; Yuan et al., 2018)
Coordination with other home care services (n = 4)	• (Mixed-)integer programming (n = 4)	• Memetic algorithm (Decerle et al., 2018) • Other heuristic algorithm (Decerle et al., 2016; Mankowska et al., 2014) • Not specified - commercially available software (Nasir et al., 2018)
Short-term fixes (n = 9)	• (Mixed-)integer programming (n = 6)	• Savings algorithm and insertion heuristics (Begur et al., 1997) • Repeated matching (Eveborn et al., 2006; Eveborn et al., 2009) • Harmony search (Lin et al., 2018) • Combination of dynamic programming and tabu search (Rest & Hirsch, 2016) • Tabu search (Yuan & Jiang, 2017)
	• Multi-agent modelling (n = 2)	• Multi-agent simulation (López-Santana et al., 2016; Marcon et al., 2017)
	• Constraint programming (n = 1)	• Combination of tabu search and adaptive large neighbourhood search (Nickel et al., 2012)
Reassessment (n = 0)	(n = 0)	–

Nahli et al., 2015), constraint programming (Nickel et al., 2012; Cattafi et al., 2015), and clustering techniques (Quintana et al., 2017). **Short-term fixes** to such solutions are also addressed in several of these publications. For instance, Lin et al. (2018) use mixed-integer programming and Nickel et al. (2012) use constraint programming, both proposing two-step approaches: the first step determining a rostering/scheduling/allocation/routing solution, the second step minimising deviations from that solution in case of disruptions. Focused on practice, Begur et al. (1997), Eveborn et al. (2006) and Eveborn et al. (2009) also use (mixed-)integer programming as a core component of interactive decision support tools producing solutions for a scheduling/allocation/routing problem and enabling the user to introduce real-time barriers downstream, with solutions automatically adapted.

Coordination of care between different professionals or different services is modelled using (mixed)-integer programming approaches and solved using bespoke heuristic algorithms (Mankowska et al., 2014; Decerle et al., 2016; Decerle et al., 2018).

3.2.4. Approaches from the non-HHC literature

In this section, we summarise our findings on OR approaches to analogous decisions in settings other than HHC. In particular, we focus on decisions that are not currently covered by the HHC literature or that are covered but might benefit from OR approaches adopted in other fields.

The problem of **service definition and access** has similarities to investment portfolio selection: choosing the set of home health care services to offer and identifying the corresponding target patients can be seen as a form of investment selection (with return expressed as a combination of monetary and utility terms) over a given planning period. Masmoudi et al. (2018) review multiple objective deterministic and stochastic programming models for this problem. The aim is to select the least risky set of investments (services in HHC settings) for a given level of return, which need not be monetary. As discussed in deLlano-Paz et al. (2017), the recent use of portfolio theory in energy planning challenges least-cost approaches that favour fossil fuels and can incorporate multiple stakeholder perspectives.

While potentially unpalatable to many working in HHC, time-of-use pricing could have useful insights for patient **screening**. For instance, Chrysopoulos and Mitkas (2018) discuss the use of multi-objective particle swarm optimisation to customise time-of-use pricing to deter some customers from requesting service at peak times.

Related to **team size and composition**, Boucher et al. (2007) survey how competence-related concepts are modelled and formalised in the literature on industrial performance improvement. This literature focuses on interaction and complementarity between team members, distinct from the HHC literature focus on just the team configurations that best meet demand. Aspects analysed include team building and competence allocation. Specifically, studies are cited that start from "Belbin's self-perception inventory" to develop formal models and/or decision support systems to assist managers in team composition (e.g. Sommerville & Dalziel, 1998; Chen & Lin, 2004).

Decisions on the **home health care plans** made for patients can be seen as analogous to the elicitation of and response to "customer requirements". A potentially relevant stream of research is that dealing with intelligent design for customised products, defined by Zhang et al. (2017) as products "designed to satisfy the customer's individual and diversified requirements as quickly and at as low a cost as possible". They cite Quality Function Deployment (Akao, 2004) as one approach to map product features to customer requirements that has been used in service design (see for instance Yan et al., 2016).

For the decision of **staff rostering**, the HHC literature found in our systematic review does not address shift design, whereas in other contexts this problem is addressed using queueing theory (Green et al., 2006) and integer programming (Ingolfsson et al., 2010).

Approaches analysing the benefits of information flow within and between organisations seem relevant to the **coordination of home care** between services. Durugbo et al. (2013) review quantitative flow analysis methods for improving organisational performance. Among the cited references, Barua et al. (1997) develop a game theory model of information exchange to analyse the exchange of usable intra- and inter-organisational information between decision units and use the idea of "cheap talk" as a mechanism for coordinating inter-organisational activities.

In our search we did not identify decisions directly analogous to the design of processes for **reassessment** of patient need. However, we consider that there are similarities to optimal control problems, consisting of designing and dimensioning interventions on a system over time (and possibly accounting for measurement uncertainties) in order to optimise the behaviour of that system. In HHC settings, such interventions would consist of updating patients' home health care plans based on changes to their health status. For instance, Büyüktahtakın and Haight (2018) reviewed such an approach in the markedly different context of invasive species management.

Finally, our search did not identify OR literature related to decisions analogous to commissioning or workforce role definition, nor work outside HHC to augment approaches to the decisions of allocation, scheduling, routing or short-term fixes.

3.2.5. Aspects of system performance in home health care

As part of the data extraction, we identified from the stated aims of each paper, or from the objective functions and constraints within the models proposed, the different aspects of the HHC system's performance considered to contribute to service quality in that paper (for instance workload balance or continuity of care).

We identified 21 different aspects of system performance and 55 different related metrics (see Appendix 2) across the 77 accepted articles. Table 3 reports the number of papers that consider each aspect for each decision problem (see Figure 1 for a definition of the decisions).

We briefly discuss below the aspects of system performance that authors use to define the quality of solutions to different decision problems and their alignment with the perspectives of different stakeholders in HHC. First, it is worth noting that over 30 of the papers reviewed explicitly consider the productivity of the staff responsible for making these decisions. This acknowledgement of the (often considerable) planning time that staff currently devote to these tasks and the extent to which this could be reduced by the adoption of OR solutions brings a focus in the literature on the process of decision support and on heuristic approaches that reduce the high computational times associated with existing solution methods (e.g. An et al., 2012; Eveborn et al., 2006).

Due to the dominance in the literature of scheduling, allocation and routing problems (usually modelled as a vehicle routing problem), staff travelling is the most represented aspect of system performance. In particular, a common objective is to minimise travelling costs (or distance, or time) incurred by the provider for daily home visits. While this reflects a provider perspective (cost minimisation), some authors augment their formulation to penalise or preclude solutions that do not take the presumed or elicited interests of patients and/or staff into account.

Patient perspectives are manifest in preferred time slots for visits ("time windows") in the model formulation, either as hard constraints (Du et al., 2017; Akjiratikarl et al., 2007), or penalties in the objective function (Braekers et al., 2016; Mankowska et al., 2014), or both (Bertels & Fahle, 2006). Overall tardiness is also used as a measure of patient experience and modelled as a component of the objective function to be minimised (Mankowska et al., 2014; Rest & Hirsch 2016). Some papers consider patients' preference for specific staff to carry out the visit (usually through penalties in the objective function) (Bowers et al., 2015; Braekers et al., 2016).

Continuity of care is another aspect of system performance important from a patient perspective. Ensuring that the same staff visit a given patient during the whole period of care can be in conflict with workload balance (staff perspective) and cost containment (provider perspective), however it has been shown that OR approaches can achieve a good level of continuity of care and a fair workload balance with limited cost increase (Carello et al., 2018). The most common measure for continuity of care is the number of staff per patient (Cattafi et al., 2015; Hewitt et al., 2016), though other metrics are also used such as number of staff deployed on tours of similar characteristics (Wirnitzer et al., 2016) or number of changes in the allocation of staff to a patient (Wirnitzer et al., 2016; Carello et al., 2018).

A related aspect of system performance that reflects a staff perspective is workload balance, with this measured in several publications through metrics such as the deviation of each member of staff's workload from average workload (e.g. Benzarti et al., 2013). Some models account directly for a staff perspective by incorporating preferences for certain patients (Hiermann et al., 2015) or penalisation of staff waiting time (Trautsamwieser et al., 2011). Also, we note that approaches that minimise staff travel time or overtime (Braekers et al., 2016) may also reflect the perspectives of some staff.

We found few papers on the commissioning of HHC and the commissioner's perspective is largely absent, although many models penalise or preclude solutions that fail to meet demand and one paper seeks to maximise the number of new patients accepted per week (De Angelis, 1998).

As with most complex systems, the models developed in HHC reflect intrinsic tensions and trade-offs between different aspects of system performance. For instance, Benzarti et al. (2013) built two complementary models to solve the districting problem: i) one minimising the maximum size of districts (seen as desirable), with constraints on the imbalance of workload between districts; ii) one minimising the maximum deviation of district workload from the average workload, with maximum district size constrained. Their results show a clear tension between the two aspects. The more common approach of combining contrasting aspects of system performance in a single objective function is exemplified in Nasir and Dang (2018), who tackle the decision of team size and composition by minimising a weighted sum of: staff travelling (measured through total distance travelled), staff costs (measured through wage costs), workload balance (measured through workload variability across staff), and demand satisfaction (measured through a cost of delaying patients).

While only a handful of papers study decisions that span different levels of planning, some aspects of system performance are considered in strategic, tactical and operational models. Specifically, staff travelling is considered in decisions of districting (Blais et al., 2003), team size and composition (Nasir & Dang, 2018), screening (Nasir & Dang, 2018) and in the vast majority of papers on rostering/scheduling/allocation/routing. In all these studies, the total distance travelled by staff is used consistently as a metric.

The level of demand satisfied is considered in models addressing decisions of screening and team size and composition (Nasir & Dang, 2018) and joint decisions of rostering, scheduling, allocation and routing (Nickel et al., 2012), using penalty costs for patient delays and unassigned visits respectively.

Workload balance among teams or individuals also features at different planning levels, with Benzarti et al. (2013) minimising the maximum deviation of district workload from the average in strategic districting decisions and Cappanera et al. (2015) maximising the minimum staff utilisation rate within a district in operational decisions of scheduling, allocation and routing.

While these single aspects of system performance appear in papers across planning levels, clustering papers by the sets of performance measures considered tended to group papers addressing similar

Table 3. Aspects of system performance.

Decision (no. papers) \ Aspect of performance (no. papers)	Continuity of care (n = 16)	Patient preferences (n = 22)	Match of staff skills to patient needs (n = 7)	District compactness (n = 1)	Number of teams (n = 2)	Budget sufficiency (n = 1)	Team size (n = 2)	Staff autonomy (n = 1)	Staff preferences (n = 13)	Costs of staff time spent with patient (n = 8)	Staff costs (n = 4)	Staff productivity (n = 7)	Staff utilisation (n = 7)	Scheduler productivity (n = 31)	Staff travelling (n = 50)	Overtime (n = 10)	Demand satisfaction (n = 12)	Disruptions to planned work (n = 3)	Punctuality (n = 5)	Synchronisation of visits (n = 1)	Workload balance (n = 14)
Definition of service and access (n = 0)																					
Districting (n = 3)	1			1	1		1							2	2						2
Screening (n = 4)											1		1		1		2		1		1
Commissioning (n = 1)						1															
Workforce roles (n = 0)																					
Team size and composition (n = 4)		1	1								3				2		2				1
Home health care plan (n = 0)																					
Staff rostering (n = 12)	4	2	1						3	1	1	1	1	6	9	3	2		1		1
Allocation of staff (n = 61)	13	22	7		1		1		13	8	3	5	5	25	45	10	9		4	1	11
Visit scheduling (n = 54)	8	22	7						13	7	3	6	5	25	45		8		4	1	6
Routing of visits (n = 55)	8	21	6		1		1		13	8	2	7	5	26	45	8	8		4	1	6
Coordination with other home care services (n = 4)		3	1							1	1			1	4				1	1	
Short-term fixes (n = 9)	2	2	3					1	3			1		4	6	1	1	3	1		
Reassessment (n = 0)																					

In the column and row names, we indicate (in brackets) the number of papers featuring each aspect of performance and each decision, respectively. See Appendix 2 and Figure 1 for definitions of the aspects of performance and decisions respectively. For each pair {decision, aspect of performance}, the table reports the number of papers modelling that decision while mentioning that aspect of performance. For instance, the aspect of performance "Overtime" appears in 10 papers: 3 dealing with staff rostering, 10 dealing with allocation of staff, 8 dealing with routing of visits, 1 dealing with short-term fixes (note that there are papers dealing with more than one decision as well as papers featuring a given aspect of performance but not modelling any of the decisions).

decision problems. Of the 10 (non-singleton) clusters of papers identified (see Appendix 3), two spanned planning levels, perhaps the most useful being a cluster of 9 papers that use a similar set of performance measures in dealing with decisions on districting and (in different combinations) rostering, scheduling, allocation and routing decisions.

3.2.6. Treatment of workforce

Part of our motivation for this review was to inform our research on workforce innovations relevant to the delivery of HHC, and so we had a particular interest in how the home care workforce was conceived within the papers reviewed. There is a range of such perspectives, reflecting differences in the nature and operations of the HHC organisations that authors were working with or studying.

Differentiation of staff by profession, seniority, qualification or mode of transport (e.g. Braekers et al., 2016) is a realistic feature of many models whereas, either because of the strategic purpose of the model or for the sake of simplicity, staff are viewed as a homogenous discrete resource (e.g. Lanzarone et al., 2010) or a homogeneous continuous (e.g. Koeleman et al., 2012) resource in others.

A key division in the literature is whether HHC staff (typically nurses) are treated as salaried employees or as a casual resource in the modelled systems. For instance, in Bard, Shao and Jarrah (2014) the nurses that deliver care are paid hourly (with differential rates per activity), with optimal route construction offering cash-releasing savings to the organisation by providing solutions in which fewer nurse shifts are used and/or nurses working shorter shifts. In such systems, nurses state their availability to work as an input and then get allotted work as an output. As an aside, forcing hierarchical binary decisions on nurses regarding their availability to work (rather than eliciting preferences for periods to work, say) could arguably lead to sub-optimal solutions for nurses and their hiring organisation.

Given the scope of the research presented in these articles, there is no consideration given to the equity of work allocation across different nurses or to the consistency of work allocated to individual nurses over time. In a context where nurses are an abundant resource, this may have no implications for the organisation, whereas if nurses are not abundant, unstable nurse incomes might make the organisation unattractive to nurses and pose a threat to services in the longer term.

In contrast, the work of Rodriguez et al. (2015) to inform the dimensioning of a salaried workforce is explicitly motivated by a wish to have a stable team of nurses, with job security implicit to this, reflecting a view in the organisation studied that this would benefit all parties.

For systems where nurses are considered permanent salaried staff, while there is some prospect of cost reduction through reduced overtime or optimal dimensioning of the workforce, the objectives of allocation, scheduling and routing models (e.g. Carello et al., 2018; Decerle et al., 2018; López-Santana et al., 2016) focus more on the opportunity costs of travel times and unutilised staff time.

Workload balance within or across teams also features in some papers (for instance Cattafi et al., 2015; Bowers et al., 2015). In the main, this is considered simply in terms of the number of visits allocated to staff, but Hertz and Lahrichi (2009) assess instead the burden that different types of case present for different grades of staff.

Another feature of modelled systems is the degree of autonomy or agency that staff have. A number of modelled systems have scope for staff to express preferences over when they work (Maya Duque et al., 2015; Bertels & Fahle, 2006). In the setting studied by Hertz and Lahrichi (2009), nurses have full autonomy over how they arrange their working day, with this precluding the development and use of centralised routing and scheduling algorithms. In other works, the modelled systems operate such that optimisation could work to the detriment of staff, for instance where staff travel costs and the time to their first appointment and home from their last appointment are not included in the objective function (e.g. Bennett & Erera, 2011) or where solutions are in line with the letter but perhaps not the spirit of working regulations (the 7-hour shifts in Cattafi et al., 2015 are partly driven by regulation that workers should have a half-hour break every 7 h).

3.2.7. Methods vs practice

Most of the papers reviewed focus on the development of new formulations and/or fast solution algorithms to better deal with model complexity. Few studies address the challenges of implementing the proposed approach in practice and the implications that these challenges have for the development of models and solution methods. We highlight some exceptions in what follows.

Although using randomly generated instances, Benzarti et al. (2013) present their work on **districting** as a decision support system for managers in HHC, envisaging that staff would interact with the tool (by modifying relevant parameters) and adapt the suggested solutions. The districting solution obtained by Blais et al. (2003) was actually adopted by their client who had provided the authors with real-world instances to validate the model.

Both works by Hindle et al. (2000; 2009) were conceived to provide health care organisations with inputs for decisions on fund allocation (**commissioning**) at national level. The former study informed yearly allocation of funds for HHC to four areas in Northern Ireland, improving existing criteria already based on OR modelling by incorporating a "rurality" feature in the model. The latter, aimed to support HHC funding allocation across districts in England, was less successful due to the low survey response rate by local authorities in providing key input data to the researchers.

Begur et al. (1997), Eveborn et al. (2006) and Eveborn et al. (2009) discuss the use of (mixed-)integer programming as a core component of interactive decision support tools producing solutions for the **scheduling/allocation/routing** problem and enabling the user to introduce real-time barriers downstream, with solutions automatically adapted (short-term fixes). In another scheduling/allocation/routing example, a HHC organisation implemented and tested the approach proposed by Maya Duque et al. (2015), in collaboration with an external software company. The authors assisted the organisation during the early stage of implementation by developing and testing a prototype of the tool. They also worked with a district manager to compare solutions from the tool with manually-generated ones and to understand the level of acceptability of the former. The organisation also provided advice during the modelling process that helped to shape the approach taken. For instance, the authors present a two-stage solution strategy not relying on Pareto-optimality criteria because the organisation considered preferences to be more important than total distance travelled. Finally, software implementing the staff allocation models developed by Lanzarone et al. (2012) was adopted by a HHC provider.

More often, algorithms in the literature were tested on simulated instances or instances generated from data provided by partner organisations. Among the latter, the model presented by Trautsamwieser et al. (2011) for rostering, scheduling, allocation and routing decisions was developed in close connection with a health care organisation with plans to include it in their decision support systems; Wirnitzer et al. (2016) mention a partnership with a home care organisation who provided a test instance and contributed to the assessment of different objective functions, one of which was used (manually) by the organisation; close collaboration with health care organisations who actively contributed to the modelling work is also mentioned in Cattafi et al. (2015), although no details were given on any implementation. Among the papers related to patient screening, only Zhang et al. (2015) mention a collaboration with an HHC organisation, which in their case provided advice on current admission policies.

4. Discussion

The strengths and weaknesses of a systematic approach to reviewing the literature are well rehearsed; while a reproducible and transparent approach to identifying papers for review, we acknowledge that search and selection of papers driven by keywords and prospective criteria can fail to identify relevant papers that could be found through other approaches. Although this has been mitigated by considering the reference lists of previous (non-systematic) review articles, we do not claim that our review contains all relevant papers. Additionally, we note that our decision framework is not exhaustive and that individuals, teams and organisations may face other decision problems specific to home health care that are amenable to Operational Research approaches. The other limitation intrinsic to our study design is that there is an inevitable degree of subjectivity in some of our interpretation of the intent and context of papers in the literature. That said, this systematic review and analysis of the OR literature on decision problems in home health care has yielded some valuable findings[1].

Previous reviews indicated that individual papers did not span the strategic, tactical and operational decisions faced in home health care. By studying the combinations and hierarchies of decision addressed in individual papers and by clustering papers that have a coherent view on system performance, one contribution of this work is to establish that there are no groups of papers that, between them, provide a comprehensive and coherent set of tools for strategic, tactical and operational decision-making in home health care. So while a home health care organisation could find approaches in the literature to problems at different planning levels, there would be no guarantee that tools chosen for operational decisions would not undermine the value of tools chosen for tactical or strategic decisions, due to the disparate aspects of system performance considered in different papers. Despite the negative results in this instance, as far as we are aware this use of clustering is novel in the context of systematic reviewing and has potential to enhance analyses of other literatures.

Other contributions of our work are that it has identified decisions in home health care amenable to operational research where there has been little or no research activity, and that is has highlighted contextual and environmental factors that should perhaps be included to enhance OR papers on home health care problems. These are presented below.

We found that the OR literature concerning HHC remains dominated by papers proposing models and solution methods for combinations of operational decisions concerning the rostering of staff, the allocation of staff to patient visits, the scheduling of visits and the routing of staff. Previous reviews (Cissé et al., 2017 and Fikar & Hirsch, 2017) have suggested a need for more stochastic formulations in such models and our review found that recent work has indeed incorporated stochastic patient demand, staff travel times and service times (for instance Shi et al., 2017a, 2017b, 2018; Yuan et al., 2018; Cappanera et al., 2018). Other advances since previous reviews include moves to explore alternative approaches to the multiple aspects of system performance acknowledged to be important in HHC, with for instance Liu et al. (2018) and Carello et al. (2018) using multi-objective optimisation, as suggested by Cissé et al. (2017). This ambition to address more of the complexity inherent in HHC systems motivates the continued focus within the literature on the development of computationally efficient solution methods.

Our analysis shows some recognition of the hierarchy of decisions in home health care with many partial hierarchies addressed, but as stated above it remains the case that papers addressing strategic, tactical and operational decisions are missing from this literature. One defence of the research community on this point would be that Operational Researchers often take the pragmatic view of wanting to build models for the problem in front of them, which typically means models that serve the explicit decisions made by the organisation or team within an organisation that they are working with and, to a greater or lesser extent, adopting the perspective of that organisation or team. Another pragmatic consideration would be that strategic decision making often has a periodicity of many years with organisations rarely receptive to solutions that involve structural change unless they arrive at the right point in this cycle, whatever the promised benefits.

This sets up a tension between the potential value of "whole supply-chain" approaches and pragmatic considerations of implementation. This would be a stronger defence if there was a greater focus on implementation in this literature, yet few papers report successful implementation in the organisations they worked with or that supplied data. Indeed, there is arguably little value to home health care in further improvement of models and solution methods without greater attention given to challenges to implementation, and we repeat the call of Fikar and Hirsch (2017) for more study of the organisational and social factors that inhibit and promote the adoption of innovations rooted in OR to decision processes in HHC.

Our review also highlights strategic and tactical decisions where there is insufficient literature. Specifically, we found little on the coordination of care across professions and organisations (although Nasir et al., 2018 make a valuable start on this), the design of contracts to support effective commissioning in HHC, the construction of home health care plans and role definitions within the workforce.

The lack of research on role definition is indicative of researchers accepting some of the choices made in HHC as fixed, or rather as not being choices. This fits a general pattern in the literature of HHC systems being presented as characterising "*the* HHC problem" rather than one instance of a HHC problem specific to the system or organisation that informed model development. For instance, models were, naturally, strongly influenced by the employment practices of the organisations studied and labour protections in place in that setting.

Other aspects of organisational context are apparent from, though not always made explicit in, descriptions of the organisational problems faced and in the models developed to address these problems. These include features of the environment in which an organisation is operating, such as whether it can choose what home care services it offers, the profiles of patient groups it accommodates or the individual patients it takes on within these groups, and what it is paid to do and on what terms. In some settings, these aspects constitute a choice of business model, in other settings they reflect the entitlements of citizens and the organisation of state provision or state funded provision. Similarly, the overarching organisational objective may be profitability, sustainability, meeting an explicit or implicit social contract, improving population health, or preventing or delaying the use of more expensive health services.

Other features often excluded from problem descriptions include the proportion of the organisation's business that is represented by HHC, or specifically whether HHC is organised independently from its other services. This is relevant when considering the value of a whole supply-chain approach because, if strategic decisions are made for a wider set of services, then good strategy may not necessarily be conducive to good operational performance in HHC services.

While the omission of these features of organisational context does not necessarily undermine the potential value of the work done for the organisations studied, it can be argued that it makes the models less generalisable (Sahin & Matta, 2015), or rather it makes it harder to understand what configurations of HHC service and in what societal settings a model could be applied or adapted.

Based on this review, we make a number of recommendations for future research. We consider that work addressing problems of role definition, home health care plan construction and contract design for commissioning would be valuable additions to the literature, as would models to support the coordination and integration of different home based health and care services. In conducting and reporting such work, we suggest that it would be beneficial for authors to align, where possible, the aspects of system performance used in objectives and constraints with those used in existing literature. This would enhance the prospects of decision makers identifying a suite of OR models that address decisions at different planning levels but that promote consistent goals. Also, as discussed above, we consider that it would be useful for authors to clarify the context of the home health care organisations that they work with such that the applicability of models to different societal settings can be more readily assessed.

Note

1. Given the elapsed time between running our literature search and publication of this article, we reran our search during the peer-review process (on the 20th January 2020) and obtained 63 additional articles, of which 34 were retained based on title/abstract. Based on information gathered from the abstracts and full-text, we found that all of the identified papers reported formulations and/or algorithms for some combination of allocation, scheduling and routing problems, except one paper presenting a formulation and an algorithm for the districting problem. We did not identify any relevant discrepancies between such additional results and the findings reported in this review.

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