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Queueing network models for the analysis and optimisation of material handling systems: a systematic literature review

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Abstract

Material handling systems (MHSs) are an integral part of logistics functions in manufacturing and service organizations. Material handling equipment (MHE) is considered the pivotal actor of any given MHS. Decisions ranging from the strategic level, such as selecting the proper MHE, capacity, and ownership (in-house or outsourcing) to operational level decisions such as resource allocation, scheduling, and routing of MHEs, are critical to the efficiency of an MHS. Industry practitioners use various methods and tools to evaluate these MHSs to find the best policies for their operations. This study identifies past works related to the performance evaluation and optimisation of MHSs using queueing network models. Moreover, this study provides a comprehensive analysis of identified research questions. The study methodology adopts a systematic literature review, bibliometric, and content analysis techniques proposed in similar research studies. This study provides material logistics scholars and practitioners with a thorough understanding of queueing networks as a modelling tool for analysing MHS applications in various domains.

Keywords MHS · Queueing networks · MHE · Performance analysis · Optimisation · Literature review

Abbreviations

ABA	Asymptotic Bound Analysis
AGV	Automated guided vehicle

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AMHS	Automated material handling system
AMR	Autonomous mobile robots
AMVA	Approximated mean value analysis
BCMP	Baskett, Chand, Muntz, Palacios
BJB	Balanced-Job-Bound
BO	Back-ordering
BOTT	BOTTAPROX method
B-PSFFA	Bi section method of point-wise stationary fluid flow approximation
CFT	Continuous flow transporters
CJN	Closed Jackson Network
CONWIP	Constant Work-In-Process
CQN	Closed queueing network
DC	Distribution centres
DSS	Decision support system
EBOTT	Extended BOTTAPROX method
ESCAT	Extended Self-Correcting Approximation Technique
ESUM	Extended Summation method
EU	European Union
FES	Flow Equivalent Server
FFS	Flexible flow shop
GA	Genetic algorithm
IB	Inbound
LAGV	Lift Automated Guided Vehicle
MAM	Matrix Analytical method
MEM	Maximum Entropy method
MGM	Matrix Geometric method
MHE	Material handling equipment
MHS	Material handling system
MIAPP	Multiple In-Aisle Pick Position
MVA	Mean value analysis
MVA-MIX	Mean value analysis–mixed networks
NILT	Narrow Aisle Lift Truck
OB	Outbound
OQN	Open queueing network
PRIOMVA	Priority mean value analysis
PRIOSUM	Priority Summation method
PSFFA	Point-wise stationary fluid flow approximation
QAG	Queue based Aggregation
QC	Quay cranes
RMFS	Robotic mobile fulfilment system
SCAT	Self-Correcting Approximation Technique
SNA	Social network analysis
SOQN	Semi-open queueing network
SUM	Summation method
SWFS	Semiconductor wafer fabrication system

WIP	Work-in-process
WS	Workstations

1 Introduction

Material handling systems (MHSs) are integral to logistics functions, enabling a smooth flow of materials to desired destinations. Material handling activities account for 15–70% of total manufacturing costs, depending on the product type (Soufi et al. 2021). Similarly, 55% of warehouse operational costs consist of material handling activities (Tompkins et al. 2010). According to Eurostat (2018), 10.8 million people employed in the warehouse-transport-storage sector account for EUR 556.0 million in the European Union (EU). Material handling systems are needed to move raw materials, work-in-progress, and finished goods from one point to another. These points include production floors, warehouses, and storage and shipping areas. Generally, the manufacturing process involves fabrication activities and assembly operations that change the material's shape, form, and make-up. In contrast, MHSs can be used to produce a "time and place utility" through the handling, storage, and control of materials (Castillo and Peters 2002; Furmans 2009).

The most critical MHS design decisions pivot around material handling equipment (MHE). Selecting the correct type of MHE and integrating it with the organisation's logistics operations are critical to the common goal of achieving low material handling costs (Cho and Egbelu 2005; Kay 2012; Rajagopalan and Heragu 1997; Stephens 2020). Kay (2012) presented ten principles compiled by the Material Handling Institute (MHI) to check when designing an MHS. Planning, standardising, work, ergonomic, unit load, space utilisation, system, automation, environmental, and life cycle principles must be considered during the MHS design process. All these are bound by MHE selection and operation. The scope of this study does not focus on selecting MHE. Instead, it deals about the performance analysis and optimisation aspects of MHEs in an MHS.

Generally, MHE can be categorised into subgroups based on its operation, technology, and application. The following categories were identified in past scientific articles: manual systems, hoists, industrial trucks, pipe systems, robotic systems, automated guided vehicles (AGVs), unit load conveyors, and bulk load conveyors (Bouh and Riopel 2016). Moreover, Smith (2013) classified MHE into three major groups: conveyors, cranes and hoists, and transporters. Conveyors transport the materials in a fixed path. Cranes and hoists are used to transfer material over a limited area. Transporters are used to carry material over a wide area. Figure 1 provides more detailed classifications of MHE (Smith 2013).

Significant design decisions regarding setting up MHSs can be categorised into the design and operation-related features. Figure 2 lists both features and their subcategories (Raman et al. 2009). Other factors that depend on specific industry needs should be considered when selecting an appropriate MHS. For instance, the semiconductor wafer fabrication system (SWFS) industry faces issues of high re-entrant flows, high level of work-in-process (WIP), flexible product routes, and longer production cycle times (Chen et al. 2017a, b). In contrast, healthcare systems face

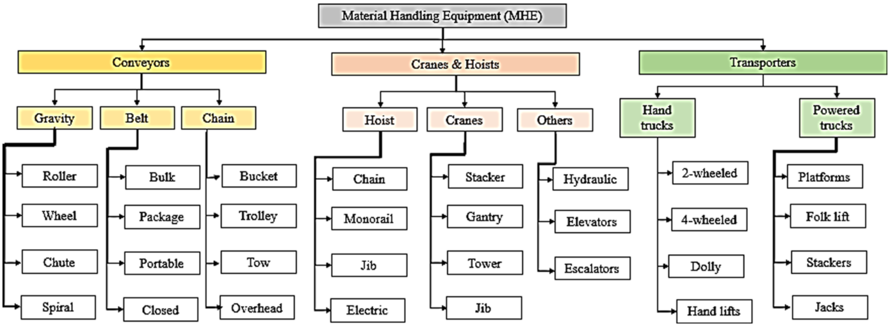

Fig. 1 MHE tree

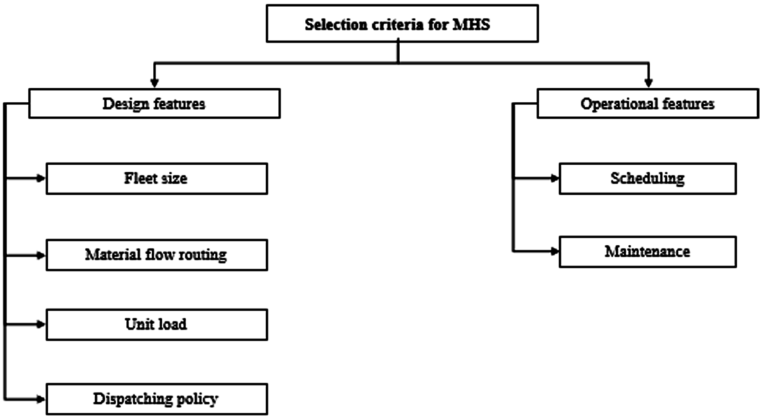

Fig. 2 Decision structure for MHS selection

unpredictable arrivals and the need for higher responsiveness. Once an organisation selects an appropriate MHS, the organisation needs to assess the performance of the MHS to measure the system's productivity. Assessing MHS performance is a critical issue that industry practitioners face (Sahu et al. 2017). Inherent variability factors such as irregular time-varying arrivals, congestions, human involvement, demand–supply fluctuations, resource breakdowns, changes in product blending, and machine capabilities may result in complications in assessing and optimising MHS performance (Lee et al. 2021).

Queueing network models are used at first to analyse and determine computer and communication systems performance measures such as mean response times, server utilisations, and queue lengths. These models have been extensively used in many other fields such as production, transportation, retail, and service industries. Queueing network models are often considered cost-effective, versatile, and powerful tools for analysing complex systems with relatively short development and computation time (Balsamo et al. 2003). The ability to inculcate finite capacity queues with blocking phenomena has made queueing network models more realistic to real-life applications in various domains. Similarly, queueing network models are used to model MHS in many supply chain nodes such as warehouses, distribution centres, intermediate storage and terminals. However, as these network models are often mathematically intractable, most studies focus on developing heuristics and approximations to determine the non-dominated performance measures (Kerbache and Smith 2004; Smith et al. 2008; Smith and Kerbache 2012).

So far, there have been very few review studies relative to queueing network modelling of MHS applications. Smith (2013) briefly mentioned MHS studies before 2012 that used a queueing network as a modelling tool. Fragapane et al. (2021) did a review study on planning and control strategies for autonomous mobile robots (AMR) in warehouses. They presented queueing networks as one of the essential tools used to model AMR systems. Gabrel et al. (2014) presented a review study on recent advances in robust optimisation where authors highlighted the use of queueing networks as a tool for stochastic optimization. Therefore, this paper provides an analysis of queueing network modelling in MHS applications by answering the following research questions:

(i) What are the queueing network models of MHS applications used for performance analysis and optimisation purposes?
(ii) What types of queues and networks are used to model MHSs?
(iii) What approaches and methodologies are used to solve the queueing network models of MHS?
(iv) What are recent trends and potential research topics about queueing network models of MHS applications?

The rest of the paper is structured as follows: Sect. 2 presents the methodology of the presented systematic review while a comprehensive bibliometric analysis is discussed in Sect. 3. Section 4 provides a content analysis of the reviewed publications. Section 5 presents the research trends and gaps found throughout this study. Finally, concluding remarks are developed in Sect. 6.

2 Research methodology

This study aims to provide a systematic review of queueing network models of MHS applications used for the purpose of analysis and optimisation. A comprehensive methodology was used to answer the identified research questions. According to Durach et al. (2021), this study used the following four (04) steps to carry out the research.

i. Formulation of research questions and keywords query

The primary goal of this step is to comprehensively search different databases to identify the relevant scientific publications that assist in answering the formulated research questions. First, journal articles, conference papers, and book chapters were gathered from the Scopus, Science Direct, and Google Scholar

Table 1 Search query

Search query
Queueing Networks
AND ("Material handling system")
AND ("warehouse", OR "distribution center" OR "manufacturing plant", OR "container terminal", OR "mining field", OR "harvest field")

Table 2 Summary of search query results

Search query	Number of publications
"queueing ?" AND "material handling ?" AND ("warehous*" OR "distribution ?")	63
"queueing ?" AND "material handling ?" AND "manufactur*"	161
"queueing ?" AND "material handling ?" AND "mining ?"	7
"queueing ?" AND "material handling ?" AND ("agriculture ?" OR "harvest ?")	4
"queueing ?" AND "material handling ?" AND "container terminal"	16
Total	251

databases. The next part of this step is to identify relevant keywords for the search. Subsequently, appropriate Boolean operators were identified and coupled with keywords to carry out a search query (Table 1). Finally, the papers containing keyword combinations in the title, abstract, and keywords were selected. The two critical areas of the study, "queueing network" and "material handling system", are included in the search query with the selected domain areas. Moreover, to capture the most number of relevant publications, keywords were used in the other possible forms (e.g., "material handling ?", "queueing network ?", queue*) in the search query. The following domains are selected to represent both goods and services production material handling activities, warehouses/distribution centres, manufacturing plants, mining fields, harvest (agriculture) fields, and container terminals.

ii. Inclusion and exclusion criteria.

The output of the initial search query and search results were summarised in Table 2. A total number of 251 publications were considered for further screening.

All duplicates were removed from the initial search. In the next step of the screening process, the studies in which queueing network models of MHS were not the primary focus of an article were removed. These exclusions included articles focused on inventory management and control, and location planning. Furthermore, only English language articles published from 2011 to 2021 were considered. Sixty-three (63) papers were selected for this study's systematic review.

iii. Analysis and results reporting.

A bibliometric analysis was carried out using these 63 papers. First, the analysis was done to identify the distribution trend of related studies over time and most sought out journals in the field. Then, an in-depth analysis was carried out to answer the identified research questions.

iv. Criterion design for in-depth analysis.

The types of MHS applications, domains, decision problems, and research methodologies were explored in this part. The criteria for the in-depth content analysis breakdown are presented in Table 3.

2.1 The criterion for the content analysis of queueing network models of MHS

This section briefly describes each criterion presented in Table 3. The comprehensive content analysis of the reviewed studies is carried out based on the above criteria. Decision problem, modelling and solution approach, performance measures, and optimisation scope are chosen to explore the reviewed studies and answer the identified research questions. Under each criterion, sub-criteria are identified, and a brief description of those are given below.

2.1.1 Scope of the study

This sub-criterion analyses the main scope of the reviewed studies. The scope of studies mainly falls into three application streams. (i). Estimate the performance of an existing system, (ii). Conceptualisation studies—estimate performance of design concepts, and (iii). optimisation studies. Moreover, some studies focus on more than one application in their work.

2.1.2 Types of queues

According to Rios Insua and Ruggeri (2012), queues can be classified based on six characteristics: namely, arrival rate, service process, number of servers, the capacity of the systems, customer population and service discipline. Smith (2013) summarises the possible queueing systems using Kendall's notation as in Table 4.

Table 3 Criteria for content analysis of queueing network models of MHS

1. Decision problem
1.1 Scope of the study
2. Modelling and solution approaches
2.1 Types of queues
2.2 Types of queueing networks
2.3 Solution approaches and methods to solve the queueing network model
3. Performance measures
3.2 Performance measures of network
4. Optimisation scope
4.1 Optimisation problem and solution approaches
4.2 Validation tools

Table 4 Structural box of queueing systems

Processes	Possible realisation
Arrival process (A)	M, D, E_k, G, GI, PH
Service process (B)	M, D, E_k, G, GI, PH
Number of servers (C)	C = 1, 2, 3, …, ∞
Capacity of the system (K)	K = 1, 2, 3, …, ∞
Population (N)	N = 1, 2, 3, …, ∞
Service discipline	FCFS, LCFS, SIRO, PR, PS, GD

M Markovian, *D* deterministic, E_k Erlang, *G* General, *GI* General independent and identically distributed, *PH* Phase distribution, *FCFS* First-come-first-served, *LCFS* Last-come-first-served, *SIRO* Server in random order, *PR* priority, *PS* processor sharing, *GD* general discipline

2.1.3 Types of queueing networks

A collection of queues is viewed as a queuing network, and these networks can be categorised based on many factors. Based on each factor, many different types of networks can be found in the literature. For instance, queueing networks can be of three types: open, closed and mixed, depending on the flows (population) circulation in the network. Similarly, many different types of networks can be found based on the network characteristics such as probability distribution, number of customer classes, the capacity of queues, number of servers and capacity of servers, and blocking mechanism. Figure 3 (Smith 2018) shows different queueing networks categorised based on the abovementioned characteristics against the network

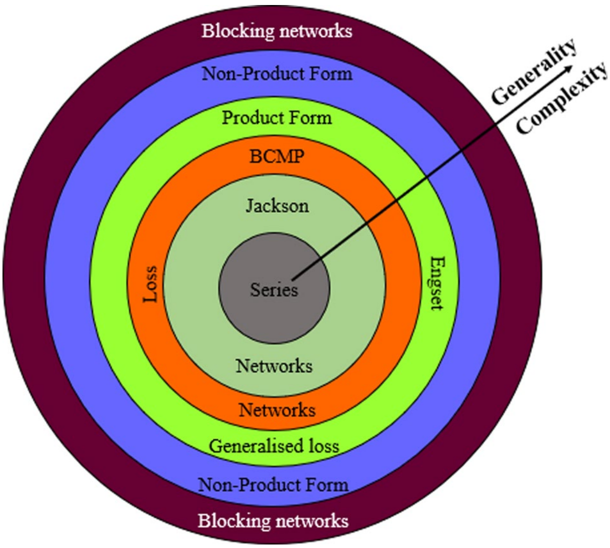

Fig. 3 Different types of queueing networks; Source: (Smith 2018)

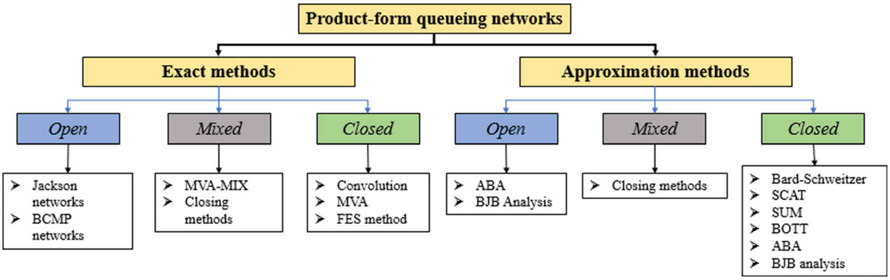

Fig. 4 Solution algorithms for product-form queueing networks. *BCMP* Baskett, Chandy, Muntz, and Palacios, *MVA-MIX* Mean Value Analysis for Mixed networks, *ABA* Asymptotic Bound Analysis, *BJB* Balanced Job Bounds, *FES* Flow Equivalent Server, *SCAT* Self-Correcting Approximation Technique, *SUM* Summation method, *BOTT* BOTTAPROX method

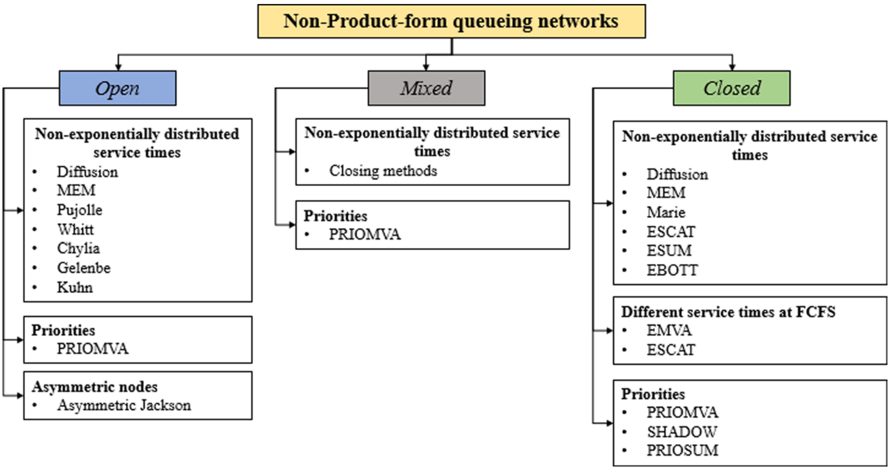

Fig. 5 Solution algorithms for non-product-form queueing networks. *MEM* Maximum Entropy Method, *PRIOMVA* Priority Mean Value Analysis, *ESCAT* Extended Self-Correcting Approximation Technique, *ESUM* Extended Summation method, *EBOTT* Extended BOTTAPROX method, *EMVA* Extended Mean Value Analysis, *PRIOSUM* Priority Summation method

complexity and generality index. However, many more types of queueing networks can be found in literature based on different characteristics.

2.1.4 Solution approaches and methods to solve the queueing network models

Depending on their mathematical complexity, queueing network models can be solved using exact analytical product form methods, approximate models, and/or simulation. Generally, smaller queueing network models can be of product form and thus, they can be solved exactly. Approximation methods are usually used for more complex queueing networks that are not of product form. Figures 4 and 5 (Bolch et al. 2006) list the exact methods and approximation approaches used to solve various queueing network models with different characteristics.

2.1.5 Performance measures of networks

Performance measures of a queueing network include measurements such as queue length, queue waiting time, queue response time, server utilisation, throughput, and cycle time (sojourn time). These measures provide invaluable insights into the decision-making processes of a given network. For instance, the throughput of a queueing network that is used to model a container terminal provides insight into the terminal's operational productivity. Similarly, the utilisation of a network node provides an idea of the congestion or idleness of that resource.

2.1.6 Optimisation problems and solution approaches

Generally, the derivation of an optimisation problem can be drawn into three parts. A planned objective/s is to be achieved by determining the optimal value of decision variable/s while satisfying the given constraints. Optimisation problems related to queueing network models of MHS can be derived similarly. Figure 6 shows the interaction between these factions. For instance, consider an optimisation problem of determining the optimal arrival rate of trucks to achieve the maximum throughput

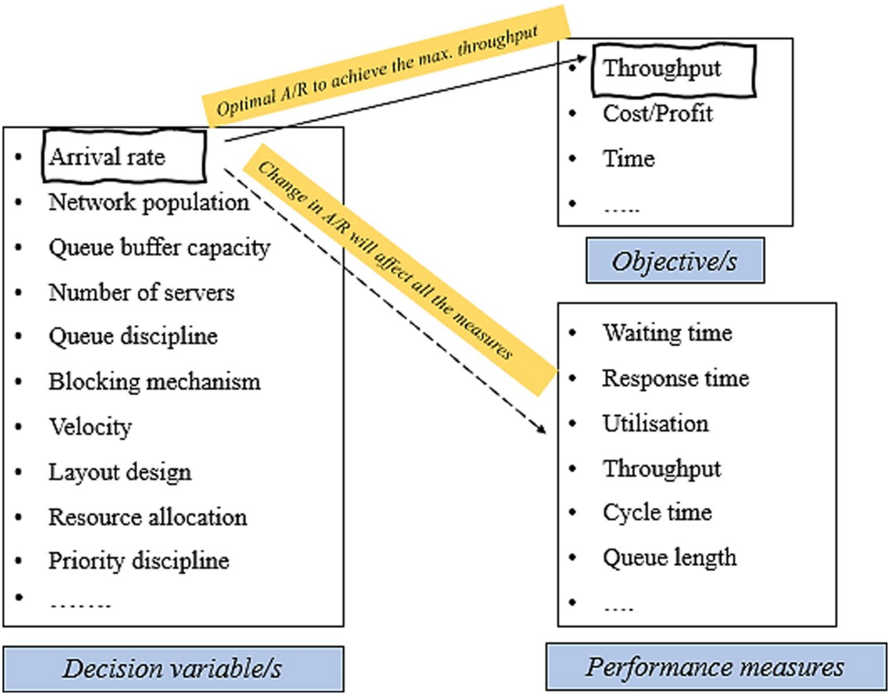

Fig. 6 Variables and parameters interaction in optimisation problem of queueing network models

in a warehouse. Subsequently, the optimal arrival rate will result in a change in all other network performance measures. Also, optimisation problems are derived as single objective or multi-objective problems. The solution approaches range from exact solution algorithms to heuristics approaches based on the complexity and magnitude of the problem.

2.1.7 Validation tools

Using approximation methods to estimate network performance measures results in possible deviations from the exact solutions. However, the validations tools are used to prove that proposed methods yield significantly similar results or that the deviations are within acceptable limits.

3 Bibliometric analysis

This section identifies the distribution trend of related studies over time and the most sought journals in the studied area. Moreover, sub-sections provide co-citation network, keywords analysis and application domain analysis to identify the trends and evolution of studies.

3.1 Publications per year

Figure 7 shows the distribution of the publications published from 2011 to 2021 that focus on queueing modelled MHS applications. The distribution indicates that from 2011 to 2020, the number of publications is consistent with an average of approximately five publications per year. However, in the last couple of years, there has been an increasing trend in the number of publications.

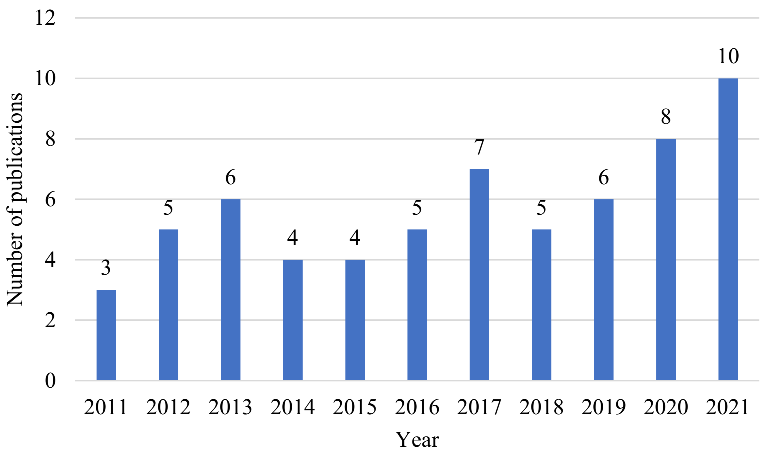

Fig. 7 Yearly distribution of publications

3.2 Publications by journal

Figure 8 shows the most important journals that published studies on queueing network models of MHS applications in various domains. More than half of (50%) the reviewed studies are from six journals. It shows that these journals are pioneers in the area of queueing network models of MHS applications related articles.

3.3 Co-citation network of publications

The co-citation network provides a visual image of the importance of reviewed publications. A connected line between two circles indicates that another publication has cited these two publications together. The sizes of frames and thickness of lines imply stronger co-citations of publications. Figure 9 shows the co-citation network of the reviewed publications based on the authors in the reviewed studies. The co-citation network visualisation map was created using VOSviewer software with the LinLog/modularity as the method option configuration. The layout was created using attraction and repulsion values of 2 and − 1, respectively. The minimum cluster size was set to 1, and the layout was allowed to merge small clusters.

3.4 High-frequency keywords

Authors use keywords to convey the primary focus of studies. Figure 10 shows a word tree map that summarises the occurrence of such words in the reviewed articles. The map was created using VOSviewer software and MS Excel. The co-occurrences of keywords are extracted using VOS viewer software. Extracted data was used to create the word tree map in MS Excel. The area of the rectangles is directly proportional to the occurrence of keywords used in the reviewed studies. In the following sub section, brief explanations of selected keywords were provided.

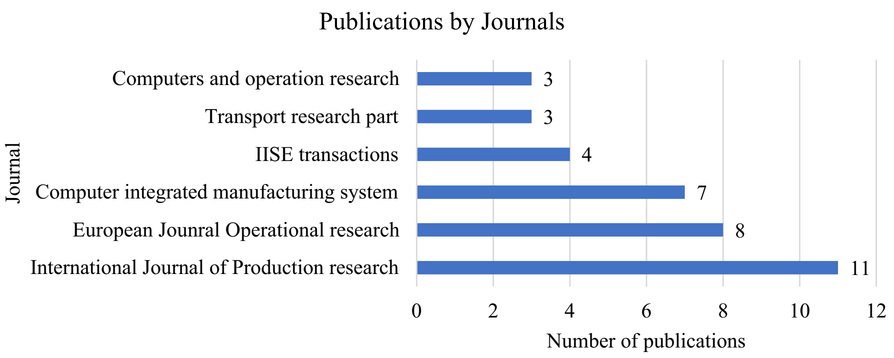

Fig. 8 Yearly distribution of publications by journal

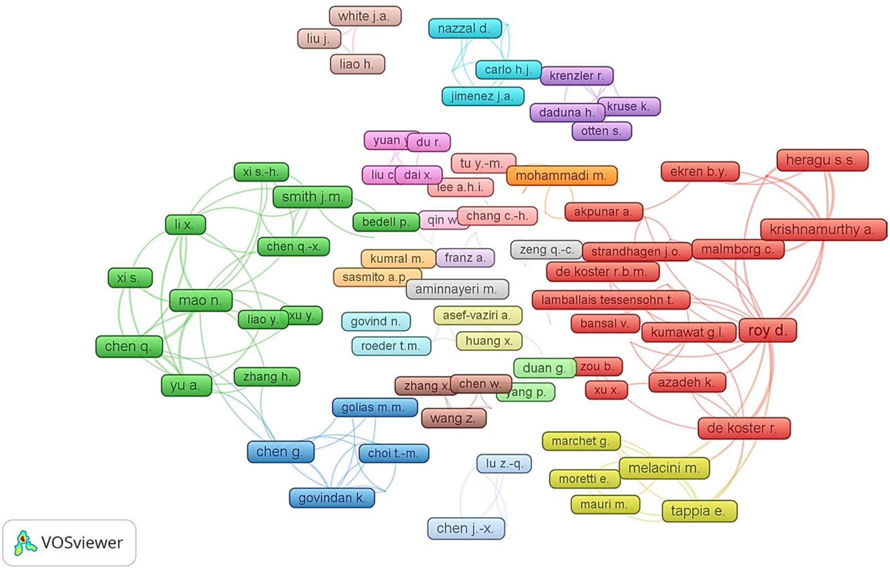

Fig. 9 Co-citation network of reviewed publications

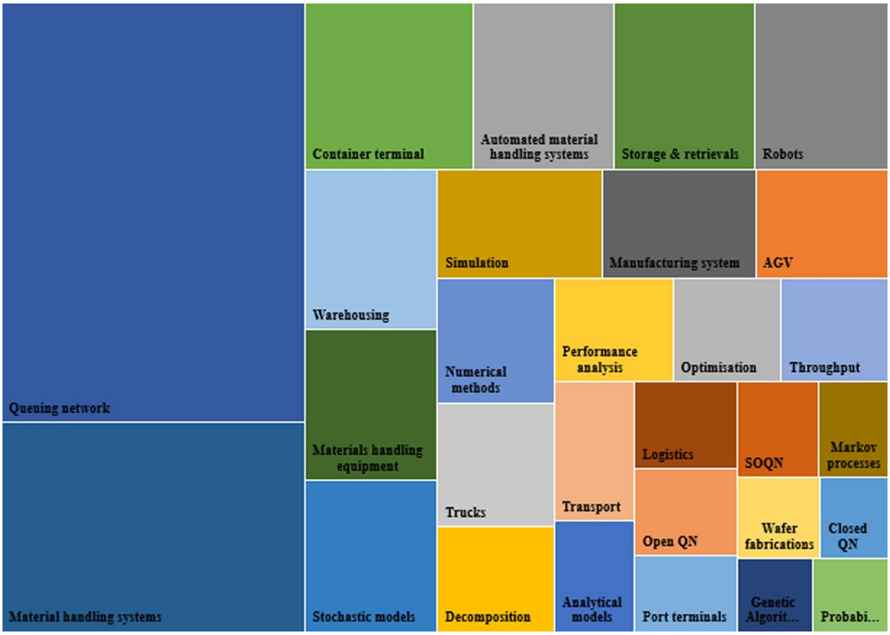

Fig. 10 Word tree map of indexed keywords

3.4.1 Open, closed, and semi-open queueing networks

An open queueing network (OQN) is where the population flow is allowed to enter and exit the network after service. In this network, the population may go through one or many nodes and finally leaves the system. A closed queueing network (CQN) is where the population flow is trapped, cyclically circulating within the network, and never leaves the network. *SOQNs, also referred to as mixed networks in the literature, are combinations of OQN and CQN, representing two types of networks in a system. Also, many studies have shown that both networks, OQN and CQN, can exist within a single system. For instance, the number of orders in a warehouse can be modelled as an OQN as orders come and go through the network without remaining in the loop. In contrast, the pickers/equipment that prepares the orders must be modelled as a CQN as they remain in the network after completing the order. Therefore, SOQNs offer a useful framework for modelling these types of mixed networks, allowing a comprehensive understanding of the system as a whole and used by many authors in their studies.* Figure 11 *provides a schematic representation of a SOQN.*

3.4.2 Decomposition

The basic concept of decomposition is to breakdown the whole network into subsystems that can be analysed individually and independently. In queueing networks, decomposition approach is a proven methodology to analyse product-form networks efficiently and parametric decomposition approach is used to analyse non-product form networks. Moreover, there are many methods and algorithms were presented in the literature that used for decomposition of queueing networks. Smith (2018) identifies the main properties of a network that enable the development of decomposition algorithms as, superposition of processes, reversibility, and splitting processes.

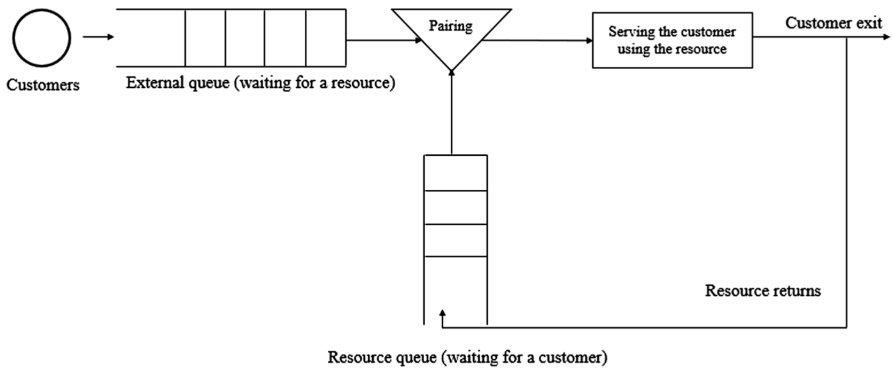

Fig. 11 A sample of a semi-open queueing network

3.5 Social network analysis (SNA) of queueing network models of MHS applications

SNA is well-suited for bibliometric clustering and conceptual model development based on the co-occurrences of keywords in the reviewed studies (Cho 2011; Jaewoo and Woonsun 2014). This tool was used to identify the current trends in the investigated study area. In this study, Mendeley and VOSviewer software are used to extract the keywords, to develop the SNA model. The frequency of the appearance and co-existence of keywords is depicted by the circle's size and links between circles. The same colours indicate that the clustering of keywords falls under similar areas of interest. Figure 12 shows the SNA of queueing network models for the MHS applications in the reviewed publications.

3.6 Number of studies according to the application domain

The selected studies are identified under four (4) domains: warehouses and distribution centres, manufacturing facilities, mining and harvesting fields, and container terminals. Figure 13 shows the number of articles under each domain used to carry out the in-depth content analysis in the following section related to the criterion identified in Table 3.

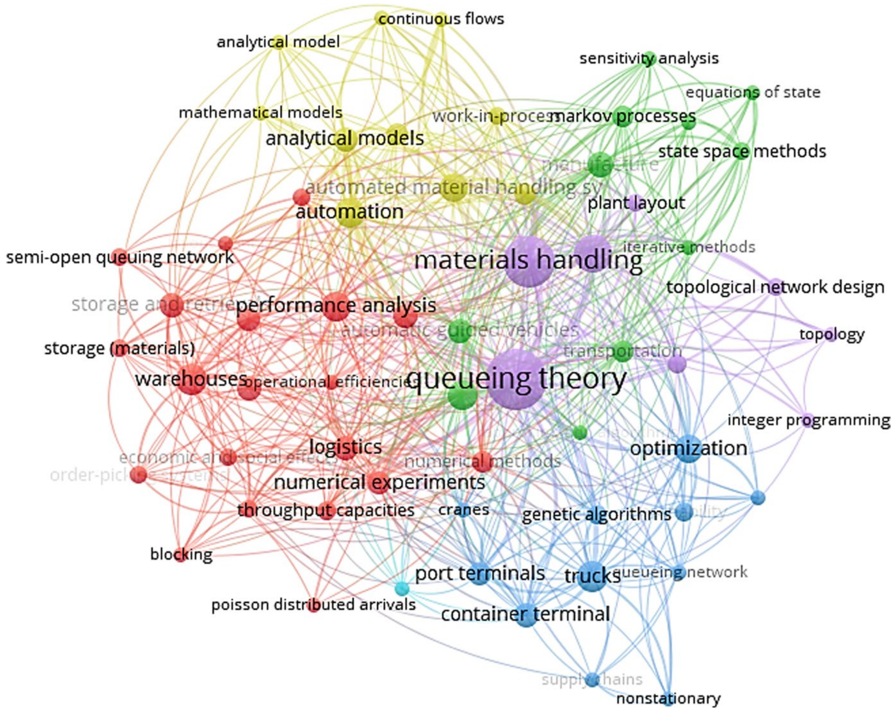

Fig. 12 SNA of queueing network models of MHS applications

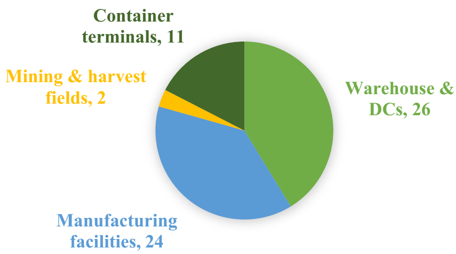

Fig. 13 Number of studies according to the application domains

4 Content analysis

This section provides an in-depth analysis of the reviewed publications based on the criteria provided in Table 3. The reviewed studies are analysed under identified domains, namely: warehouses and distribution centres, manufacturing facilities, mining and harvesting fields, and container terminals.

4.1 Queueing network models of MHS applications in warehouses and distribution centres

Conventional warehouses and distribution centres (DCs) provide "time and place utility" for products and raw materials in a value chain. Modern warehouses and DCs are designed to create value by performing postponement, value addition, and cross-docking processes. Material handling is one of the key cost components of warehouse operations and is labour intensive. Material handling systems evolved from human-powered to semi-automated and then fully automated systems. Modern warehouses are typically fully or partially automated to increase storage and picking efficiency. Compact storage systems are famous for low unit-load demand and high space utilization. Different types of handling systems that allow movement along the x, y, and z-axes for compact storage systems are classified as conveyor-based (using cranes) and shuttle-based (using cranes and lifts) (Tappia et al. 2017). An automated vehicle system/retrieval system (AVS/RS) is a shuttle-based handling system used in compact storage systems with single deep racks (Heragu et al. 2011). Automated handling systems, which can move along a free path, are known as automated guided vehicles (AGVs).

4.1.1 Decision problems of queueing network models of MHS applications in warehouses and DCs

Table 5 lists the study's scope in the reviewed publications related to warehouses and DCs. Performance measurement studies are carried out to evaluate the performance of the existing facilities concerning single or many design parameters. In contrast, conceptualisation studies are done in the planning stages of building or outsourcing a facility to estimate the system's performance. Similarly,

Table 5 Scope of the reviewed studies in the field of warehouses and DCs

References	Scope of the study
Heragu et al. (2011)	Design conceptualisation—evaluate of alternate facility configurations
Marchet et al. (2012)	Performance measurement of existing layout arrangement and fleet
Roy et al. (2012)	Conceptualisation—optimal design criteria
Schleyer and Gue (2012)	Optimal batch size for maximised throughput
Roy et al. (2014)	Conceptualisation—evaluate design trade-offs
Ekren et al. (2014)	Performance measurement
Seyedhoseini et al. (2015)	Minimize transportation and operation costs through layout design
Roy et al. (2015a)	Evaluate cross-aisle locations and dwell policies
Roy et al. (2015b)	Evaluate congestion effects on storage and retrieval process
Yuan and Gong, (2016)	Determine robot's velocity and fleet size for a desired order cycle time
Motaghedi and Aminnayeri (2017)	Determine waiting time for trucks
Tappia et al. (2017)	Design conceptualisation—evaluate of alternate facility configurations
Zou et al. (2018)	Determine optimal strategy between battery swapping or charging
Motaghedi and Aminnayeri (2018)	Determine optimal number of outbound doors (servers) in cross dock
Azadeh et al. (2019)	Determine optimal system layout for maximum throughput
Tappia et al. (2019)	Evaluate CONWIP
Wang et al. (2020)	Evaluate throughput and cycle time in an existing facility
Lamballais et al. (2020)	Determine the number of stock locations for existing S/R policies
Liu et al. (2020)	Performance measurement
Shen et al. (2021)	Performance measurement of different operating policies
Lamballais et al. (2021)	Determine resource allocation during peak and off-peak periods
Yang et al. (2021)	Determine throughput, utilisation, and queue length
Duan et al. (2021)	Determine resource allocation during peak and off-peak periods
Ekren and Akpunar (2021)	Determine design parameters number of bays, aisle, and tiers
Otten et al. (2021)	Determine minimum number of robots needed for a desired service level
Liu et al. (2021)	Performance measurement of RMFS

optimisation studies are also carried out with existing facilities or based on the conceptualisation of facilities.

4.1.2 Modelling and solution approaches of queueing network models of MHS applications in warehouses and DCs

Heragu et al. (2011) and Marchet et al. (2012) modelled an AVS/RS as an open queueing network to analyze the system's performance. The orders are considered as the network customers. Moreover, the AVS/RS was modelled as a multi-class, semi-open queueing network (SOQN) to measure the system's performance and determine the warehouse's design criteria and resource allocation (Ekren et al. 2014; Roy et al. 2012, 2015b). Roy et al. (2014) modelled an AVS/RS as a SOQN with a blocking phenomenon to estimate performance. Schleyer and Gue (2012) modelled a picking process in a warehouse with a single picker as a queueing network model to estimate the throughput time for a stationary order arrival system. Roy et al. (2015a) modelled an AVS/RS as a continuous system as a SOQN in a multi-tiered warehouse.

Seyedhoseini et al. (2015) modelled inbound (IB) and outbound (OB) trucks as two Markovian queues in a cross-docking warehouse set up to determine the optimal design needed to minimize transportation costs. Motaghedi and Aminnayeri (2017, 2018) modelled a cross-dock in a supply chain using a non-stationary queueing model, a novel approach, to estimate design layout efficiency.

Yuan and Gong (2016) used non-Markovian queues to model an order fulfilment system operated by robots to estimate the throughput of the system and determine the optimal number of robots for a desired level of service. Zou et al. (2018) modelled a robotic mobile fulfilment system (RMFS) in a warehouse using a single queuing system and used a nested SOQN to model the battery swapping process. Shen et al. (2021) modelled a drone fleet that serviced a multi-warehouse system as a closed queueing network (CQN) and a battery swap process as a SOQN to estimate performance measures.

A multi-tiered warehouse with a shuttle-based storage and retrieval system (SBS/RS) with lifts was modelled as a SOQN to measure system performance (Tappia et al. 2017). Azadeh et al. (2019) modelled an automated storage and retrieval (AS/R) system run by robots using a CQN to estimate the maximum system throughput under different blocking protocols. Tappia et al. (2019) compared the performance of a shuttle-based and automated handling system using queueing models. Wang et al. (2020) and Lamballais et al. (2020) modelled RMFSs as an OQN and SOQN, respectively, to estimate performance measures. Yang et al. (2021) and Duan et al. (2021) used SOQNs to model a multi-deep RMFS and RMFS with time-varying arrivals. To determine the optimal fleet size, Otten et al. (2021) modelled an RMFS as a SOQN with a back-ordering (BO) phenomenon. Ekren and Akpunar (2021) used an OQN to model an SBS/RS that handled mini unit loads. Lamballais et al. (2021) modelled a handling system run by robots and humans as a SOQN to find the optimal resource allocation for the picking and replenishment activities.

In another study, a case-level order picking process in a multiple in-aisle picking position (MIAPP) system operated with a narrow-aisle lift truck (NILT) was modelled as an M/G/1/K/N queue (Liu et al. 2020) and as M/G/1/K (Liu et al. 2021) queue to estimate performance measures.

Table 6 summarises the queue types and employed solution approaches for solving the network in MHS applications in warehouses and DCs in the reviewed studies.

4.2 Queueing network models of MHS applications in manufacturing environments

Generally, a manufacturing system's physical configuration encompasses an arrangement of workstations (WS), machines, and other types of equipment in

Table 6 Modelling and solution approach analysis of models in warehouses and DCs

References	Queue type	Solution approach to solve the queueing network model
Heragu et al. (2011)	GI/G/C	Parametric decomposition; used MPA software for calculation
Marchet et al. (2012)	M/G/1	Parametric decomposition; Method of Whitt (1983) and Approximation by Allen
Roy et al. (2012)	M/D/1	Decomposition approach; solved with Convolution algorithm
Schleyer and Gue (2012)	G/G/1	Method of Grassmann and Jain (1989) to calculate the waiting time
Roy et al. (2014)	M/D/1	Decomposition approach, solved with Convolution algorithm
Ekren et al. (2014)	G/PH/1	Aggregation method; solved with Matrix Geometric Method (MGM)
Seyedhoseini et al. (2015)	M/M/C	Numerical method
Roy et al. (2015a)	M/D/1	Decomposition approach; solved with AMVA algorithm
Roy et al. (2015b)	M/D/1	Decomposition approach, solved with Convolution algorithm
Yuan and Gong (2016)	G/M/1	Methods from Whitt (1983) algorithm to determine the expected delay
Motaghedi and Aminnayeri (2017)	Δ(i)/d/1*	An exact method used to compute the waiting time based on order statistics
Tappia et al. (2017)	GI/G/1	Parametric decomposition; solved with MGM
Zou et al. (2018)	M/G/1	Parametric decomposition; solved with MGM
Motaghedi and Aminnayeri (2018)	Δ(i)/d/1*	Waiting time is calculated based on order statistics along with the Bayes theorem
Azadeh et al. (2019)	M/D/∞	Decomposition approach; solved with AMVA algorithm
Tappia et al. (2019)	GI/G/1	Decomposition approach; solved with MVA algorithm
Wang et al. (2020)	M/G/1	Parametric decomposition; Method of Whitt (1983)
Lamballais et al. (2020)	M/G/1	Decomposition approach; solved with AMVA algorithm
Liu et al. (2020)	M/G/1/K/N	Matrix Analytical method (MAM); use of Chebyshev travel metric method
Shen et al. (2021)	M/D/1	Decomposition approach; solved with AMVA algorithm
Lamballais et al. (2021)	M/G/1	Decomposition approach; solved with AMVA algorithm
Yang et al. (2021)	M/M/∞	Decomposition approach; solved with AMVA algorithm
Duan et al. (2021)	M/G/1	Parametric decomposition; solved with MGM
Ekren and Akpunar, (2021)	G/G/C	Decomposition approach; Method of Whitt (1983) algorithm

Table 6 (continued)

References	Queue type	Solution approach to solve the queueing network model
Otten et al. (2021)	M/G/1/∞	Decomposition approach; Norton theorem and Convolution algorithm
Liu et al. (2021)	M/G/1/K	Matrix Analytical method (MAM); use of Chebyshev travel metric method

*Non-stationary queues

various layouts that are physically connected by the MHE (ElMaraghy et al. 2021). The imperious fluctuations of global trade demands and associated uncertainty necessitate a manufacturing system's responsiveness. Material handling configuration plays a crucial role in the process, and material handling cost is one of the critical indicators of a manufacturing facility's efficiency (Amjath et al. 2022; Besbes et al. 2021). Arrangements of workstations, aisle structure, and positions of machines influence material handling costs (Pourvaziri et al. 2021).

4.2.1 Decision problems of queueing network models of MHS applications in manufacturing environments

During the last decade, many studies have been conducted using queueing networks to determine the optimisation and performance evaluation of MHS in various manufacturing environments, including fabrication plants, workstations (WS), assembly lines, job shops and flexible flow shops (FFS). Table 7 lists the

Table 7 Scope of the reviewed studies in the field of manufacturing facilities

References	Scope of the study
Govind et al. (2011)	Calculate WIP and queue delays
Nazzal, (2011)	Estimates throughput capacity
Raman, (2011)	Determine layout and fleet size based on WIP
Choobineh et al. (2012)	Determine optimal fleet size based on throughput
Sukhotu and Peters (2012)	Identify performance measurements with WS arrangement
Smith and Kerbache (2012)	Analysis of different Network topologies
Bedell and Smith (2012)	Analysis of different Network topologies
Tu et al. (2013)	Analysis performance measures with capacity of AMHS
Chen and Zhou (2013)	Calculate WIP with layout changes
Zhou and Chen (2013)	Calculate WIP
Tu and Chang (2014)	Determine the bottleneck and queue time
Zhu and Wu (2014)	Determine optimal design considering vehicle blocking
Smith and Barnes (2015)	Determine optimal server allocation according to the topology
Zhou et al. (2015)	Identify performance measurements considering priority rules
Smith (2016)	Determine optimal buffer allocation and network population
Zhou et al. (2016)	Calculate WIP considering priority rules
Xu et al. (2016)	Determine system design and resource allocation
Xi et al. (2017a)	Determine the optimal resource allocation for an assembly system
Xi et al. (2017b)	Determine the optimal buffer allocation based on WIP
Chen et al. (2017a, b)	Capacity planning for wafer fabrication plant based on WIP
Chen et al. (2017a, b)	Estimate performance measurements
Liao et al. (2017)	Identify performance measurements considering uncertainty
Mohammadi et al. (2020)	Estimate product cycle time
Zhang et al. (2021)	Estimate performance measurements

scope of reviewed studies of queueing network models of MHS in various manufacturing environments.

4.2.2 Modelling and solution approaches of queueing network models of MHS applications in manufacturing environments

Work-in-process (WIP) is one of the key performance indicators of the efficiency of an MHS in a manufacturing environment. Govind et al. (2011) used a CQN to model the inter-bay AMHS of a semiconductor manufacturing system and estimate the queue delays and WIP levels. A multi-vehicle AMHS was modelled as a closed-loop queueing network with a finite buffer to estimate the throughput capacity considering the stochastic loading and unloading time (Nazzal 2011). Tu et al. (2013) proposed a queueing model for the AMHS of a semiconductor manufacturing system to estimate the required number of MHEs. Zhou and Chen (2013) modelled an AMHS of a semiconductor wafer fabrication system using a finite Markovian queueing model to estimate the expected WIP when considering crossovers. A multi-class non-Markovian infinite queueing model was proposed for continuous flow transporters (CFTs) in a semiconductor manufacturing system with a non-pre-emptive priority rule to estimate the WIP in the material intersection points (Zhou and Chen 2013). A GI/G/M queueing model was used to determine the capacity of an AHMS in a semiconductor manufacturing system (Tu and Chang 2014). Zhu and Wu (2014) modelled an AMHS in a semiconductor wafer fabrication system while using the vehicle blocking phenomenon and a queueing network to estimate performance measures. As part of an AMHS in a semiconductor manufacturing facility, a CFT was modelled with priority rules to estimate the WIP (Zhou et al. 2015, 2016). In a semiconductor manufacturing facility, Chen et al. (2017a, b) modelled an AMHS as an OQN and service stations as infinite Markovian queues under uncertain wafer lots transfer probability to estimate the WIP level.

WIP is a critical factor in a manufacturing system, and WIP accumulation can occur for various reasons. Raman (2011) used the queueing theory to estimate the WIP and server utilization while considering manufacturing variability. The author used the WIP to determine the optimal layout and fleet size using the Genetic Algorithm (GA) and the two-step analytical approach. Choobineh et al. (2012) modelled an MHS with AGVs using a multi-class CQN and used the state-dependant behaviour of the network to determine the optimal fleet size.

Sukhotu and Peters (2012) modelled a multi-class MHS with a job-specific routing using queues with non-Poisson arrival rates and generally independent and identically distributed service time, to analyse the effect of workstation arrangements in a manufacturing facility. Smith and Kerbache (2012) and Bedell and Smith (2012) proposed a state-dependent multi-server queueing network with a finite buffer to estimate the performance of an MHS under different network topologies such as series, merge, and split configuration. Smith and Barnes (2015) and Smith (2016) modelled an MHS using a CQN with a finite buffer to determine the optimal buffer allocation and network population.

The design of an MHS in a flexible flow shop (FFS) is one of the critical factors to be considered when deciding on the layout design, resource allocation, and design criteria. Xu et al. (2016) modelled the MHS of an FFS in a mould manufacturing facility with a random lot size using an OQN with a finite buffer to determine system design and resource allocation. Liao et al. (2017) used an OQN with a finite buffer to model an FFS with non-equivalent AGVs to estimate system performance considering manufacturing uncertainty and random lot size. Zhang et al. (2021) modelled an integrated production and the MHS of an FFS using an OQN with blocking after service (BAS) blocking to estimate performance measurement.

Xi et al. (2017a) modelled an assembly manufacturing system with bulk transportation using a queueing network to study the impact of buffer allocation on the system's performance. The authors determine the optimal WIP and fleet size to minimize the total investment cost. Xi et al. (2017b) modelled a customized assembly manufacturing system with an OQN with a finite buffer and blocking consideration to estimate the MHS's efficiency.

Chen et al. (2017a, b) used an OQN with a finite buffer to model an MHS with AGVs to estimate the performance indexes in a manufacturing system. Mohammadi et al. (2020) presented a novel queue-based aggregation (QAG) model to estimate the performance of an AMHS in a multi-product job shop facility.

Table 8 summarises the queue types and employed solution approaches for solving the network in MHS applications in manufacturing facilities in the reviewed studies.

4.3 Queuing network models for MHS applications in mining and harvesting systems

Munoz and Lee (2021) presented a study where queues in the mill and harvest front of a sugarcane harvesting system were modelled as two independent queues to estimate the system's performance. The authors used a node diagram and balance equations to solve the closed network model and used performance measures to determine the optimal number of trucks for smoother operation. Sembakutti et al. (2017) studied the problem of equipment (shovel and trucks) allocation in an earth and surface mining pit. To estimate the truck waiting time and queue length, they modelled the operations using a model with 'Generally defined distribution" arrivals and service times.

Tables 9 and 10 summarise the scope and queue types and employed solution approaches for solving the network in MHS applications in mining and harvest fields, respectively.

4.4 Queueing network models of MHS applications in container terminals

Container terminals are one of the critical nodes in global trading that have radically changed over time. Integration between seaside and landside activities is vital to the efficiency of terminal operations. Adequately planning the MHS, including quay cranes, yard cranes, yard trailers, and trucks, is critical to a smooth terminal operation and a lower turnaround time for container ships (Li and He 2021).

Table 8 Modelling and solution approach analysis of models in manufacturing facilities

References	Queue Type	Solution approach to solve the queueing network model
Govind et al. (2011)	M/G/C	Simulation
Nazzal (2011)	G/G/C	Iterative algorithm to solve the model
Raman (2011)	G/G/C	Queueing theory
Choobineh et al. (2012)	M/M/1	Calculated steady-state performance measures using transition probabilities
Sukhotu and Peters (2012)	GI/G/1	Parametric decomposition; Method of Whitt (1983) algorithm
Smith and Kerbache (2012)	M/G/C/C	Decomposition approach; solved with GEM
Bedell and Smith (2012)	M/G/C/C	Decomposition approach; solved with MVA algorithm
Tu et al. (2013)	GI/G/C	Parametric decomposition; Method of Whitt (1983) algorithm
Chen and Zhou (2013)	M/M/1/K	Continuous Time Markov Chain (CTMC)—Steady state behaviour
Zhou and Chen (2013)	M/G/1	Decomposition approach; solved with AMVA algorithm
Tu and Chang (2014)	GI/G/C	Decomposition approach; Method of Whitt (1983) algorithm
Zhu and Wu (2014)	M/M/1/K	Parametric decomposition
Smith and Barnes (2015)	M/G/C/C	Decompose approach; solved with MVA algorithm
Zhou et al. (2015)	M/G/1	Parametric decomposition; Matrix Analytical Method (MAM)
Smith (2016)	M/G/C/C	Decompose approach; solved with MVA algorithm
Zhou et al. (2016)	GI/G/1	Queueing theory—CTMC
Xu et al. (2016)	M/G/1	State space method for decomposition
Xi et al. (2017a)	M/G/1/K	State space method for decomposition
Xi et al. (2017b)	M/G/1/K	State space method for decomposition
Chen et al. (2017a, b)	M/M/1	Parametric decomposition; Flow balance equations
Chen et al. (2017a, b)	M/M/1	Parametric decomposition; State space method
Liao et al. (2017)	M/M/1/K	Improved state space decomposition method
Mohammadi et al. (2020)	GI/G/C	Queue-based aggregation (QAG) model
Zhang et al. (2021)	M/G/C/K	State space method for decomposition

Table 9 Scope of the reviewed studies in the field of mining and harvest fields

References	Scope of the study
Sembakutti et al. (2017)	Determine the optimal resource allocation/Match factor to minimise waiting time
Munoz and Lee (2021)	Determine the optimal fleet size

Table 10 Modelling and solution approach analysis of models in mining and harvest fields

References	Queue type	Solution approach to solve the queueing network model
Sembakutti et al. (2017)	G/G/C	Parametric decomposition; Method of Whitt (1983) algorithm
Munoz and Lee (2021)	GI/G/1	Parametric decomposition; using Node diagram and balance equations

4.4.1 Decision problems of queueing network models of MHS applications in container terminals

Stakeholders' interests in container terminal operations differ from one another. The vessel operators desire for lowest waiting time, and terminal operators are staking for maximum throughput. The throughput is considered a container terminal operator's main performance index. Similarly, trucks or trailers are aiming for the lowest cycle time. Queueing network models are used from different stakeholders' perspectives in the reviewed studies. Table 11 lists the purpose of the studies related to the queueing network models of MHS applications in container terminals.

4.4.2 Modelling and solution approaches of queueing network models of MHS applications in container terminals

Chen et al. (2013a) modelled a terminal gate operation using a non-stationary queueing network to determine the optimal number of trucks that need to be allowed at any given time to reduce the truck queue length. The authors experimented with two scenarios, static and dynamic terminal appointment systems, to find the optimal truck arrival rate. Chen et al. (2013b) used a queueing network to model a terminal gate system to find the optimal truck arrival pattern needed to reduce carbon emissions from idling trucks. Chen et al. (2013c) used a queueing model to estimate truck queue length to minimize the congestion at a terminal gate. Zeng et al. (2016) used a vacation queueing model to model IB and OB trucks to determine the optimal truck appointment policy. Dhingra et al. (2018) used a SOQN to model trucks arriving at an automated container terminal at various times to estimate the number of trucks to be permitted in the terminal. Ansorena (2020) used a closed Jackson network (CJN) approach to study port operations and determine truck congestion.

Roy and de Koster (2018) modelled overlapping quay crane (QC) and automated stacking crane (ASC) operations as an OQN and a SOQN to analyse

Table 11 Scope of the reviewed studies in the field of container terminals

References	Scope of the study
Chen et al. (2013a)	Determine optimal number of trucks per hour to reduce the truck queue length
Chen et al. (2013b)	Optimise truck arrival patterns to reduce emissions
Chen et al. (2013c)	Control truck arrivals to reduce congestion at the gate
Zeng et al. (2016)	Determine optimal truck appointment for outbound and inbound operations
Dhingra et al. (2018)	Regulate the number of trucks for resource allocation and demand levelling
Roy and de Koster (2018)	Analyse the performance of overlapping loading and unloading operations
Zhang et al. (2019)	Determine optimal truck allocation to minimize cost under double cycling
Ansorena (2020)	Analysis of stowage and traffic impact on port productivity
Roy and de Koster (2020)	Estimate maximum throughput considering stack layout arrangements
Legato and Mazza (2020)	Determine performance measurement of terminal operations
Kumawat and Roy (2021)	Design criteria decision on comparing performance of LAGVs and AGVs

performance. The authors suggested that layout planning is paramount for single and overlapping operation efficiency. Zhang et al. (2019) used a queueing network to model the double cycling operation of a container terminal. The authors used the queuing model to identify the system bottleneck and server utilization (QC, yard cranes, trucks) and determine the optimal truck allocation to minimize the terminal operation cost. Roy and de Koster (2020) used a CQN to model yard operations and a SOQN to model landside operations to find the maximum throughput based on a stacking layout. Legato and Mazza (2020) used a CQN and an OQN to model yard and seaside operations to estimate the terminal performance. Finally, Kumawat and Roy (2021) used a SOQN to model the sea-to-shore operations in a container terminal to compare the performance of AGVs and LAGVs.

Table 12 summarises the queue types and employed solution approaches for solving the network in MHS applications in container terminals in the reviewed studies.

4.5 Performance measures of queueing network models

Assessment of queueing model performance measures plays a crucial role in managing and controlling the networks. Measuring the system's performance is always a key objective of queueing network models. There are mainly identified performance measures of queueing network models: utilisation, throughput, response time, waiting time, cycle time, queue length, and the number of jobs in the system. Depending on the system, specific performance measures play a crucial role in understanding the system's behaviour.

Table 13 summarises the key performance measures of queueing network models used in the reviewed studies.

4.6 Optimisation problems and solution approaches

Queueing network models are used to design optimisation problems in MHS applications in various domains, improve existing configurations, or design new systems. Queueing network models are extensively used to model stochastic models and proved to be a robust tool in optimisation. Optimisation problems under queueing network models of MHS can be categorised into a few application streams. The identified application streams can be categorised into layout design and configuration problems, fleet sizing and allocation problems, determination of customer/job arrival rates and scheduling problems, and server and buffer allocation problems. Table 14 summarises the optimisation problems identified in the reviewed studies along with the problem objective, decision variables and solution approach. Figure 14 provides the dendrogram of keywords used in the optimisation studies of queueing network models of MHS. These diagrams show the hierarchical clustering of indexed keywords to identify different classification criteria (Aria and Cuccurullo 2017).

Table 12 Modelling and solution approach analysis of models in container terminals

References	Que. Type	Solution approach to solve the queueing network model
Chen et al. (2013a)	$M_{(t)}/E_{k(t)}/C_{(t)}$	B-PSFFA method to solve the model
Chen et al. (2013b)	$M_{(t)}/G/C_{(t)}$	B-PSFFA method to solve the model
Chen et al. (2013c)	$M_{(t)}/E_{k(t)}/C_{(t)}$	B-PSFFA method to solve the model
Dhingra et al. (2018)	GI/G/1	Decomposition approach; solved with MGM
Roy and de Koster (2018)	GI/G/1	Iterative algorithm for decomposition; Whitt (1983) algorithm
Zhang et al. (2019)	M/D/1	PSFFA method to solve the model
Ansorena (2020)	M/M/1/K	Flow balance and flow conservation equations are used to determine throughput
Roy and de Koster (2020)	GI/G/1	Parametric decomposition approach; Whitt (1983) algorithm
Legato and Mazza (2020)	GI/G/1	State dependent exponential distribution (SDED) method for decomposition
Kumawat and Roy (2021)	M/G/1	Network aggregation dis-aggregation approach; AMVA algorithm

B-PSFFA Bi section method of Point-wise stationary fluid flow approximation

Table 13 Identified performance measures in the reviewed studies

References	Performance measures				
	Throughput	Utilisation	Waiting time	Cycle time	Queue length
Govind et al. (2011)			✓	✓	✓
Heragu et al. (2011)	✓	✓	✓		✓
Nazzal (2011)	✓				✓
Raman (2011)		✓		✓	✓
Bedell and Smith (2012)	✓		✓	✓	✓
Choobineh et al. (2012)	✓	✓	✓		
Marchet et al. (2012)		✓	✓		
Roy et al. (2012)		✓	✓	✓	
Schleyer and Gue (2012)	✓	✓	✓	✓	
Smith and Kerbache (2012)	✓		✓		✓
Sukhotu and Peters (2012)		✓	✓	✓	✓
Chen et al. (2013a)			✓		✓
Chen et al. (2013b)		✓	✓	`	✓
Chen et al. (2013c)			✓		✓
Chen and Zhou (2013)		✓			✓
Tu et al. (2013)	✓	✓		✓	
Zhou and Chen (2013)					✓
Ekren et al. (2014)		✓	✓		✓
Roy et al. (2014)		✓		✓	✓
Tu and Chang (2014)			✓	✓	
Zhu and Wu (2014)		✓		✓	
Roy et al. (2015a)		✓		✓	✓
Roy et al. (2015b)		✓		✓	✓
Seyedhoseini et al. (2015)			✓		
Smith and Barnes (2015)	✓		✓		✓
Zhou et al. (2015)					✓
Smith (2016)	✓		✓	✓	✓
Xu et al. (2016)		✓	✓	✓	
Yuan and Gong (2016)			✓		
Zeng et al. (2016)			✓		
Zhou et al. (2016)		✓	✓		✓
Chen et al. (2017a, b)					✓
G. Chen et al. (2017a, b)		✓		✓	✓
Liao et al. (2017)		✓		✓	✓
Motaghedi and Aminnayeri (2017)			✓		
Sembakutti et al. (2017)			✓	✓	
Tappia et al. (2017)	✓	✓			✓
Xi et al. (2017a)	✓				✓
Xi et al. (2017b)	✓				✓
Dhingra et al. (2018)					✓
Motaghedi and Aminnayeri (2018)			✓		✓

Table 13 (continued)

References	Performance measures				
	Throughput	Utilisation	Waiting time	Cycle time	Queue length
Roy and de Koster (2018)	✓				
Zou et al. (2018)	✓	✓	✓		
Azadeh et al. (2019)	✓	✓		✓	
Tappia et al. (2019)	✓		✓		
Zhang et al. (2019)	✓	✓			✓
Ansorena (2020)		✓			
Lamballais et al. (2020)	✓	✓	✓		
Liu et al. (2020)			✓	✓	
Legato and Mazza (2020)		✓	✓	✓	✓
Mohammadi et al. (2020)	✓		✓	✓	
Roy and de Koster (2020)		✓		✓	✓
Wang et al. (2020)	✓		✓	✓	
Duan et al. (2021)	✓		✓	✓	✓
Ekren and Akpunar (2021)	✓		✓	✓	✓
Kumawat and Roy (2021)	✓	✓	✓	✓	✓
Lamballais et al. (2021)	✓		✓		
Liu et al. (2021)			✓	✓	✓
Munoz and Lee (2021)			✓	✓	
Otten et al. (2021)	✓		✓	✓	
Shen et al. (2021)	✓				
Yang et al. (2021)	✓	✓			✓
Zhang et al. (2021)	✓	✓			✓

4.6.1 Layout design and configuration problems

Layout designs are closely related to the performance of an MHS in any intra-logistics setup. Many studies in the reviewed articles were found related to determining the optimal layout design and configuration for a given facility to achieve the desired objective/s, such as maximum throughput, minimum cycle time or minimising the cost of operations. Raman (2011) developed an optimisation problem to determine the optimal layout plan and fleet size to minimise the WIP level in a semiconductor fabrication facility. Zhu and Wu (2014) modelled a warehouse facility using the finite queueing system to find the optimal layout configuration. The authors used the study to find the optimal number of aisles, aisle width, and rack configurations to minimise the blocking and congestion effect in the order picking process. Seyedhoseini et al. (2015) presented an optimisation problem to find the optimal number of doors in a cross-docking warehouse to minimise the waiting time of trucks. Motaghedi and Aminnayeri (2018) and Azadeh et al. (2019) used the queueing network models of MHS to determine the optimal layout design to minimise the waiting time and maximise throughput, respectively.

Table 14 Optimisation study analysis of queueing network models of MHS

References	Objective/s	Decision variable/s	Solution approach
Raman (2011)	Minimise WIP	Layout plan and fleet size	Queueing theory and GA based approach
Choobineh et al. (2012)	Minimise server utilisation	Fleet size	Linear programming
Schleyer and Gue (2012)	Minimise throughput time	Batch (load) size	Discrete time queue models
Chen et al. (2013a)	Minimise queue length	Arrival rate	Hybrid algorithm using GA and simulated annealing
Chen et al. (2013b)	Minimise waiting/idle time	Arrival rate	GA based heuristics
Chen et al. (2013c)	Minimise queue length	Arrival rate	GA based heuristics
Zhu and Wu (2014)	Minimise blocking effect	Design configuration	Analytical model based on SOQN
Seyedhoseini et al. (2015)	Minimise transportation cost	Layout configuration and fleet size	Mixed integer model with queueing theory
Smith and Barnes (2015)	Maximise throughput	Number of servers	Non-linear branch-and-bound algorithm based on SQP
Smith (2016)	Maximise throughput	Buffer size and population	Non-linear SQP approach
Yuan and Gong (2016)	Minimise throughput time	Fleet size and velocity	Queueing theory
Zeng et al. (2016)	Minimise congestion	Truck appointment/schedule	GA based approach
Xi et al. (2017a)	Maximise throughput	Resource allocation	Branch and bound optimisation method
Xi et al. (2017b)	Minimise WIP	Buffer allocation	Branch and bound optimisation method
Zou et al. (2018)	Minimise cost	Battery swapping strategy	Analytical model based on SOQN
Motaghedi and Aminnayeri (2018)	Minimise waiting time	Layout design	Queueing system with order statistics
Azadeh et al. (2019)	Maximise throughput	Design configuration	Analytical model based on CQN
Zhang et al. (2019)	Minimise operational cost	Truck allocation	Scheduling and allocation optimisation algorithm
Roy and de Koster (2020)	Maximise throughput	Stack layout configuration	Analytical model based on queueing network models
Munoz and Lee (2021)	Minimise cycle time	Fleet size	Model built on queueing approximation formulas
Otten et al. (2021)	Minimise lost customers	Fleet size	Analytical model based on SOQN

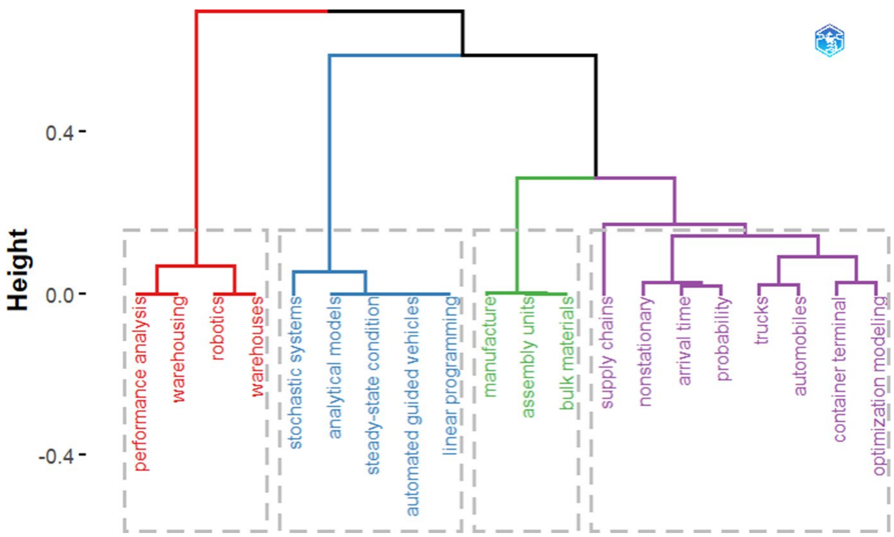

Fig. 14 Dendrogram of hierarchical cluster analysis of optimisation problems

Roy and de Koster (2020) presented a study to determine a container terminal's optimal stack layout configurations to maximise the berth throughput.

4.6.2 Fleet sizing and allocation problems

In a closed or mixed queueing network, the population is a critical factor that influences the performance measures of the network. An overcrowded population/customers can create longer waiting times in queues, whereas a low number of customers in the network can result in the under-utilisation of servers. Choobineh et al. (2012) presented a study to determine the optimal number of AGVs in a manufacturing environment to achieve the desired level of throughput. Yuan and Gong (2016) modelled a robotics warehouse to determine the optimal robots and the velocity of the robots to minimise the order throughput time. Zhang et al. (2019) carried out a study to determine the optimal truck allocation in a container terminal to minimise the cost while ensuring truck allocation reduces the double handling of the containers. Munoz and Lee (2021) presented a study to determine the optimal fleet size of trucks in a sugarcane harvest field to ensure an uninterrupted operation. Otten et al. (2021) modelled an automated robotics warehouse considering the back-ordering phenomenon to find the optimal number of robots required to minimise the lost customers. Schleyer and Gue (2012) developed a study to find the optimal load size of an AGVs to minimise the order throughput time in a warehouse.

4.6.3 Arrival rates and scheduling problems

Arrival rates and inter-arrival rates are paramount to network performance measures. The probability distribution of arrival patterns of customers/jobs is a significant basis for the queueing system classification. Chen et al. (c, 2017a), , , , 2013b, , , conducted studies to determine the optimal inbound truck arrival rate in a container terminal to minimise the queue length, carbon emissions, and congestion, respectively. Zeng et al. (2016) developed an optimal truck appointment schedule to reduce congestion at a gate in the container terminal.

4.6.4 Server and buffer allocation problems

The number of servers and buffer sizes are essential factors in a finite queueing system. With the evolution of queueing network model analysis, practitioners started to use more realistic models where the number of servers and queue capacities are limited. These finite networks with multiple server's environment result in non-product form networks which need approximation algorithms to solve. Smith and Barnes (2015) presented a study to determine the optimal number of servers in a manufacturing setup to maximise the system's throughput. Smith (2016) conducted a study to find the optimal buffer and population to maximise the throughput of a given facility. Xi et al. (2017a) studied bulk material transportation in an assembly process to find the optimal resource (server) allocation strategy to maximise the line's throughput. Xi et al. (2017b) further developed the study to find the optimal buffer allocation strategy to minimise the infrastructure configuration investment cost and WIP level.

4.7 Simulation as a validation tool

Generally, queues and queueing networks are complex systems and are possible to tractable when assumptions are made to simplify them. However, most of the assumptions may not precisely describe the actual system properties and features. Therefore, most of the studies focus on developing approximation algorithms and heuristics approaches to tackle the solving of these queueing network models. In such situations, simulation tools are used to validate the accuracy of the proposed methodologies. Table 15 summarises the details of the simulation tools and experiments used in the reviewed studies. The simulation run column contains the general information on the number of replications, run time and warm-up period. Replications are used to ensure the stability of the model, and warm-up period data is excluded from calculation due to the transient state of the model in the initial stages of the run. Generally, steady-state data is used in the simulation model for performance measures calculations.

5 Trends in queueing network models for MHS applications

Figure 15 shows the trend topics plot of study areas of queueing network models for MHS applications within the last decade. This plot is created using the bibliometrix software package with the bibiloshiny application (Aria and Cuccurullo 2017). The trend topic plot shows the most frequently appeared keywords in the relevant

Table 15 Simulation software and experiments details of reviewed studies

References	Simulation software	Run time		
		Replications	Run time	warm-up period
Heragu et al. (2011)	Arena 12.0	100	1100 h	100 h
Marchet et al. (2012)	Arena 13.0	20	48 h	3 h
Roy et al. (2012)	AutoMod software	15	600 h	120 h
Roy et al. (2014)	AutoMod software	15	24,000 units	5000 units
Ekren et al. (2014)	Arena 12.0	10	2 years	3 months
Roy et al. (2015a)	AutoMod software	15	600 h	120 h
Roy et al. (2015b)	AutoMod software	15	20,000 units	2000 units
Tappia et al. (2017)	Arena 14.7	15	25,000 units	5000 units
Zou et al. (2018)	Arena 14.8	100	1000 h	100 h
Azadeh et al. (2019)	AutoMod software	40		
Tappia et al. (2019)	Arena	15	1,250,000 s	250,000 s
Wang et al. (2020)	Arena	30	72 h	
Lamballais et al. (2020)	Java	10	168 h	56 h
Liu et al. (2020)	Monte Carlo simulation	100	500 h	50 h
Shen et al. (2021)	Arena	30	240 h	24 h
Lamballais et al. (2021)	RAWSim-O	10	1 year	
Duan et al. (2021)	Java	100	168 h	
Otten et al. (2021)	SimPy 3.0	20	365 days	
Govind et al. (2011)	SIGMA	10	100,000 units	
Choobineh et al. (2012)	SIMAN		100,000 min	
Sukhotu and Peters (2012)	Arena	40		
Smith and Kerbache (2012)	Arena	30	100,000 units	1000 units
Bedell and Smith (2012)	Arena	30	120,000 units	20,000 units
Tu et al. (2013)	eM-Plant 7.0	50	60 days	30 days
Smith (2016)	Arena	30	100,000 units	1000 units
Mohammadi et al. (2020)	Anylogic	20	15,000 units	1500 units
Zhang et al. (2021)	SIEMENS	50	100,000 units	2000 units
Dhingra et al. (2018)	Arena 14.0	25	1000 days	500 days
Roy and de Koster (2018)	AutoMod software	15	480 h	24 h
Kumawat and Roy (2021)	Arena	10	10 days	1 day

periods, and the area of the circle on the timeline is proportional to the frequency of appearances.

In the initial period, most studies focus on the MHS applications regarding layout design and planning. Similarly, topological network design problems of facilities were modelled and analysed using queueing network models. Also, queueing network models were used for continuous systems in contrast to discrete systems, such as conveyor belt modelling. In early 2013, manufacturing facilities and container terminals' intra-logistics operations were modelled using queueing networks for performance analysis. WIP was identified as one of the critical

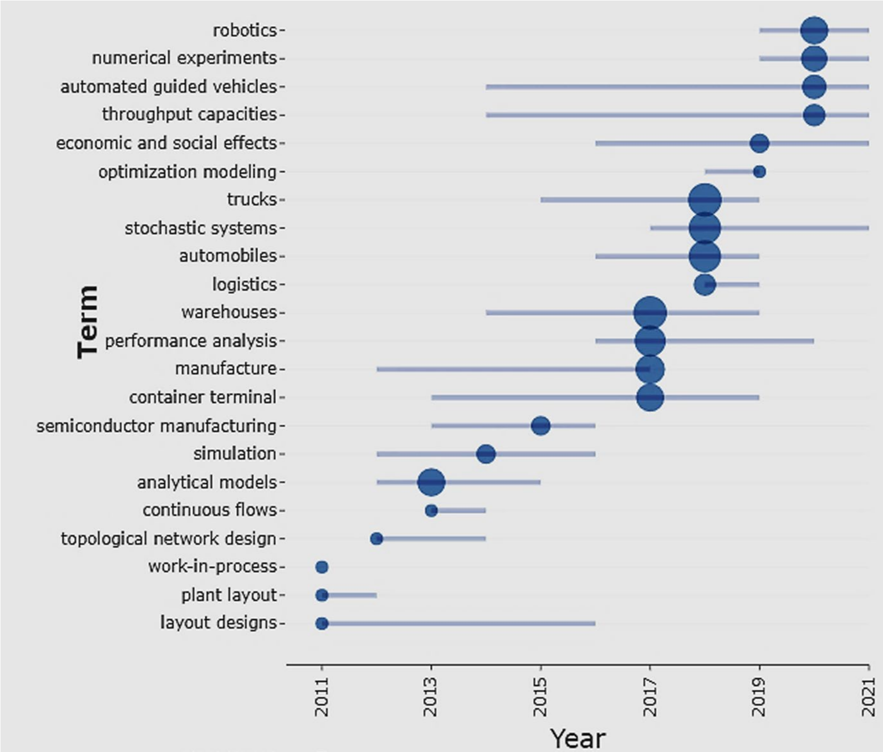

Fig. 15 Trend topics of queueing network models of MHS applications between 2011 and 2021

performance measures in analysing the performance of manufacturing facility material handling operations. Studies related to the semiconductor manufacturing facility's material handling systems were in constant interest between 2013 and 2016 to analyse the efficiency of their MHS. The studies on terminal operations in ports started using queueing network models to study and analyse the behaviour of outbound and inbound truck arrivals concerning cost, congestion and emission.

The operation of trucks and automobiles was one of the major topics studied using queueing network models during 2015–2018. Warehouse operations also used queueing network models to analyse the system performance and optimisation purposes. Determination of throughput capacities of facilities seems to be one of the significant explored performance measures in the recent past. Around 2016, queueing network models were used to analyse automated MHS applications such as AGVs and robots. With the evolution of studies in queueing network models of MHS applications, the optimisation modelling was coupled with queueing models to find the system's optimum. Also, the focuses of such optimisation studies tend to include social effects in their problem formulations. Using numerical experiments and methods in optimisation has been a critical observation in the last few years.

6 Discussion

Scholars and industry practitioners have recognized that material handling is one of the most critical logistic functions in the manufacturing and service sectors. Companies employ different approaches and methods to ensure the efficient flow of materials and minimize the cost of handling operations. This study presents a systematic literature review on the performance evaluation and optimization of MHS applications, primarily using queueing networks as the modelling tool in various domains. A total of 63 studies published from 2011 to 2021 were systematically and meticulously analysed to understand the queueing network models of MHS applications comprehensively.

A bibliometric analysis indicated that the number of publications published on the subject is generally consistent throughout time but increased in 2020 and 2021. Moreover, few journals stand out from the rest regarding the number of queueing-based MHS application-related publications. The co-citation networks based on authors, word tree map of keywords, SNA model, trend topic plots and dendrogram were developed to identify trends and patterns in the queueing network models of MHS.

Content analysis showed four main application domains studied in the reviewed publications: warehouses and DCs, manufacturing systems, container terminals, and mining/harvest fields. Queueing networks were used in studies to model the MHSs in these domains, evaluate system performances, and decoupled with analytical models to optimise selected parameters. The performance measures presented in the studies were throughput, cycle time (sojourn time), server utilisation, queue length, WIP, and waiting time. Depending on the application domain and scope of the study, the authors determined the required performance measures by solving the queueing network models. Regarding the optimisation of the systems, most of the reviewed studies focused on maximising throughput under different constraint conditions. Several studies focused on minimising cycle time, waiting time, and WIP levels. These parameters were primarily coupled with the objective cost or revenue functions. A select number of studies focused on determining the optimal population (fleet size), buffer size, or arrival rate of the network's customers to achieve desired objectives such as minimal cost, maximum profit/revenue, or minimal cycle time. Some studies regarding MHS applications in warehouses were used to determine design configuration criteria such as aisle width, the distance between racks, the height of racks, and the number of loading/unloading bays and routing topologies. Similarly, a few studies in the manufacturing domain were used to determine the optimal number of workstations, layout configurations, and routing plans for MHEs. In general, studies related to container terminals focus on IB and OB truck management.

There was evidence that modelling approaches have been becoming complex with time to emulate the real world systems to their closest. Use of finite queueing systems, inculcating blocking mechanisms in the queues, multi-server networks with asymmetric nodes, including non-Markovian properties in the queueing systems, and implementation of advance queue disciplines, have been used in the models of MHS applications. However, Smith (2018) points out certain types of networks have not been used in modelling MHS applications, such as loss networks and Engset networks.

There are also chronological patterns that can be seen in the types of MHS applications studied. For instance, many studies modelled robotics and AGVs of MHSs as queueing networks for analysis and optimisation purposes during 2019–2021. Similarly, the focus of studies tends to change from performance analysis problems to optimisation modelling problems.

There is potential for developing a decision support system (DSS) for designing and operating an MHS using queueing network models. The abovementioned studies primarily focus on the MHS design problems from a uni-dimensional perspective. For instance, a study that focuses on layout topologies to maximise the throughput without concentrating on the cost of fleet, the congestion, and resource utilisation. Therefore, the challenge is to develop multicriteria decision support systems to design and operate optimal MHS configurations in a given supply chain domain. Moreover, the study and analysis of asymmetric and heterogeneous nodes in networks remain limited in queueing network models relative to MHS applications. In contrast, they are abundantly used in analysing computing and communication network applications.

6.1 Conclusion

The use of queueing networks to model material handling systems in various intralogistics domains has significantly helped academics and industry practitioners to study and analyse complex system topologies and behaviours. The coupling of queueing networks with numerical methods and approaches has undeniably helped to improve and optimise the studied systems. As pointed out in the discussion, the complexity of networks has been increasing with time, and novel approaches to solving models have been reported in the literature. Moreover, these studies have focused more on automated and integrated systems in the recent past. However, the queueing network models of MHS are yet to be systematically used as robust decision support systems in designing optimal MHS topologies in organisation setups. As presented in this study, most surveyed queueing network models focus on single criteria analysis and optimisation. However, an organisation can potentially use the queueing network models as a robust tool in all strategic, managerial and operational decision-making processes in designing and operating its MHS.

Author contributions All authors contributed to the study idea. MA: performed the literature search, data collection and analysis. Supervision was provided by LK, AE and JMS. The first draft of the manuscript was written by MA, and all authors commented on previous versions. All authors read and approved the final manuscript.

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Data availability We confirm all data, materials and software applications comply with field standards.

Code availability Not applicable.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval We confirm that this work is the result of original research and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

References

Amjath M, Kerbache L, Macgregor J, Elomri A (2022) Fleet sizing of trucks for an inter-facility material handling system using closed queueing networks. Oper Res Perspect 9(April):100245. https://doi.org/10.1016/j.orp.2022.100245

Ansorena IL (2020) Operational strategies for managing container terminals. An approach based on closed queuing networks. Int J Ind Syst Eng 35(1):13–27. https://doi.org/10.1504/IJISE.2020.106847

Aria M, Cuccurullo C (2017) bibliometrix: An R-tool for comprehensive science mapping analysis. J Informet 11(4):959–975

Azadeh K, Roy D, De Koster R (2019) Design, modeling, and analysis of vertical robotic storage and retrieval systems. Transp Sci 53(5):1213–1234. https://doi.org/10.1287/trsc.2018.0883

Balsamo S, De Nitto Personè V, Inverardi P (2003) A review on queueing network models with finite capacity queues for software architectures performance prediction. Perform Eval 51(2–4):269–288. https://doi.org/10.1016/S0166-5316(02)00099-8

Bedell P, Smith JM (2012) Topological arrangements of M/G/c/K, M/G/c/c queues in transportation and material handling systems. Comput Oper Res 39(11):2800–2819. https://doi.org/10.1016/j.cor.2012.02.009

Besbes M, Mahjoub YI, Bonte T, Berger T, Sallez Y, Zolghadri M (2021) Solving Facility Layout Problem with safety consideration of Reconfigurable Manufacturing and Assembly Systems. Procedia CIRP 104:1942–1947. https://doi.org/10.1016/j.procir.2021.11.328

Bolch G, Greiner S, De Meer H, Trivedi KS (2006) Queueing networks and Markov chains: modeling and performance evaluation with computer science applications. John Wiley and Sons

Bouh MA and Riopel D (2016) Material handling equipment selection: New classifications of equipments and attributes. In: Proceedings of 2015 International Conference on Industrial Engineering and Systems Management, IEEE IESM 2015, October, 461–468. https://doi.org/10.1109/IESM.2015.7380198

Castillo I, Peters BA (2002) Unit load and material-handling considerations in facility layout design. Int J Prod Res 40(13):2955–2989

Chen G, Govindan K, Golias MM (2013a) Reducing truck emissions at container terminals in a low carbon economy: proposal of a queueing-based bi-objective model for optimizing truck arrival pattern. Transp Res Part E 55:3–22. https://doi.org/10.1016/j.tre.2013.03.008

Chen G, Govindan K, Yang Z-Z, Choi T-M, Jiang L (2013b) Terminal appointment system design by non-stationary M(t)/E k/c(t) queueing model and genetic algorithm. Int J Prod Econ 146(2):694–703. https://doi.org/10.1016/j.ijpe.2013.09.001

Chen G, Govindan K, Yang Z (2013c) Managing truck arrivals with time windows to alleviate gate congestion at container terminals. Int J Prod Econ 141(1):179–188. https://doi.org/10.1016/j.ijpe.2012.03.033

Chen G, Chen Q, Mao N, Yu A, Zhang H (2017a) Modeling and analysis of queuing network in manufacturing system with stochastic path AGV. Jisuanji Jicheng Zhizao Xitong 23(1):52–65. https://doi.org/10.13196/j.cims.2017.01.007

Chen W, Wang Z, Chan FTS (2017b) Robust production capacity planning under uncertain wafer lots transfer probabilities for semiconductor automated material handling systems. Eur J Oper Res 261(3):929–940. https://doi.org/10.1016/j.ejor.2017.02.026

Cho C, Egbelu PJ (2005) Design of a web-based integrated material handling system for manufacturing applications. Int J Prod Res 43(2):375–403. https://doi.org/10.1080/0020754042000268866

Cho I, Kim N (2011) Recommending core and connecting keywords of research area using social network and data mining techniques. J Intell Inf Syst 17(1):127–138

Choobineh FF, Asef-Vaziri A, Huang X (2012) Fleet sizing of automated guided vehicles: a linear programming approach based on closed queuing networks. Int J Prod Res 50(12):3222–3235. https://doi.org/10.1080/00207543.2011.562560

Dhingra V, Kumawat GL, Roy D, Koster RD (2018) Solving semi-open queuing networks with time-varying arrivals: an application in container terminal landside operations. Eur J Oper Res 267(3):855–876. https://doi.org/10.1016/j.ejor.2017.12.020

Duan G, Zhang C, Gonzalez P, Qi M (2021) Performance evaluation for Robotic Mobile Fulfillment Systems with time-varying arrivals. Comput Ind Eng. https://doi.org/10.1016/j.cie.2021.107365

Durach CF, Kembro JH, Wieland A (2021) How to advance theory through literature reviews in logistics and supply chain management. Int J Phys Distrib Logist Manag 51(10):1090–1107. https://doi.org/10.1108/IJPDLM-11-2020-0381

Ekren BY, Akpunar A (2021) An open queuing network-based tool for performance estimations in a shuttle-based storage and retrieval system. Appl Math Model 89:1678–1695. https://doi.org/10.1016/j.apm.2020.07.055

Ekren BY, Heragu SS, Krishnamurthy A, Malmborg CJ (2014) Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system. Comput Ind Eng 68(1):78–86. https://doi.org/10.1016/j.cie.2013.12.002

ElMaraghy H, Monostori L, Schuh G, ElMaraghy W (2021) Evolution and future of manufacturing systems. CIRP Ann 70(2):635–658. https://doi.org/10.1016/j.cirp.2021.05.008

Eurostat (2018) Database—Eurostat. https://ec.europa.eu/eurostat/web/main/data/database

Fragapane G, Roy D, Sgarbossa F and Strandhagen JO (2021) Planning autonomous material transportation in hospitals. In Dolgui A, Bernard A, Lemoine D, von Cieminski G, Romero D (eds) IFIP WG 5.7 International Conference on Advances in Production Management Systems, APMS 2021: Vol. 632 IFIP (pp 24–32). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-030-85906-0_3

Furmans K (2009) Material handling and production systems modelling: based on queuing models. Springer

Gabrel V, Murat C, Thiele A (2014) Recent advances in robust optimization: an overview. Eur J Oper Res 235(3):471–483

Govind N, Roeder TM, Schruben LW (2011) A simulation-based closed queueing network approximation of semiconductor automated material handling systems. IEEE Trans Semicond Manuf 24(1):5–13. https://doi.org/10.1109/TSM.2010.2089659

Heragu SS, Cai X, Krishnamurthy A, Malmborg CJ (2011) Analytical models for analysis of automated warehouse material handling systems. Int J Prod Res 49(22):6833–6861. https://doi.org/10.1080/00207543.2010.518994

Insua DR, Ruggeri F (eds) (2012) Robust bayesian analysis. Springer

Jaewoo C, Woonsun K (2014) Themes and trends in Korean educational technology research: a social network analysis of keywords. Procedia Soc Behav Sci 131:171–176. https://doi.org/10.1016/j.sbspro.2014.04.099

Kay MG (2012) Material handling equipment. In: Fitts Dept. of Industrial and Systems Engineering North Carolina State University, 65

Kerbache L, Smith JM (2004) Queueing networks and the topological design of supply chain systems. Int J Prod Econ 91(3):251–272

Kumawat GL, Roy D (2021) AGV or Lift-AGV? Performance trade-offs and design insights for container terminals with robotized transport vehicle technology. IISE Trans 53(7):751–769. https://doi.org/10.1080/24725854.2020.1785648

Lamballais T, Merschformann M, Roy D, de Koster MBM, Azadeh K, Suhl L (2021) Dynamic policies for resource reallocation in a robotic mobile fulfillment system with time-varying demand. Eur J Oper Res. https://doi.org/10.1016/j.ejor.2021.09.001

Lamballais Tessensohn T, Roy D, De Koster RBM (2020) Inventory allocation in robotic mobile fulfillment systems. IISE Trans 52(1):1–17. https://doi.org/10.1080/24725854.2018.1560517

Lee S, Lim D-E, Kang Y, Kim HJ (2021) Clustered multi-task sequence-to-sequence learning for autonomous vehicle repositioning. IEEE Access 9:14504–14515

Legato P, Mazza RM (2020) Queueing analysis for operations modeling in port logistics. Maritime Bus Rev 5(1):67–83. https://doi.org/10.1108/MABR-09-2019-0035

Li B, He Y (2021) Computational logistics for container terminal handling systems with deep learning. Comput Intell Neurosci. https://doi.org/10.1155/2021/5529914

Liao Y, Chen Q, Mao N, Yu A, Li X (2017) Modelling and analysis of queueing network in flexible flow shop with non-equivalent parallel AGVs. Jisuanji Jicheng Zhizao Xitong 23(9):1950–1961. https://doi.org/10.13196/j.cims.2017.09.014

Liu J, Liao H, White JA (2021) Queueing analysis of the replenishment of multiple in-the-aisle pick positions. IISE Trans 53(1):1–20. https://doi.org/10.1080/24725854.2020.1731773

Liu J, Liao H and White Jr., JA (2020) Queueing analysis of a class-based MIAPP-NALT order-picking system. In: C. L., S. R., and W. P. (eds) 2020 Institute of Industrial and Systems Engineers Annual Conference and Expo, IISE 2020 (pp 1306–1311). Institute of Industrial and Systems Engineers, IISE

Marchet G, Melacini M, Perotti S, Tappia E (2012) Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes. Int J Prod Res 50(24):7134–7148. https://doi.org/10.1080/00207543.2011.639815

Mohammadi M, Dauzère-pérès S, Yugma C, Karimi-Mamaghan M (2020) A queue-based aggregation approach for performance evaluation of a production system with an AMHS. Comput Oper Res. https://doi.org/10.1016/j.cor.2019.104838

Motaghedi-Larijani A, Aminnayeri M (2017) Optimizing the admission time of outbound trucks entering a cross-dock with uniform arrival time by considering a queuing model. Eng Optim 49(3):466–480. https://doi.org/10.1080/0305215X.2016.1206414

Motaghedi-Larijani A, Aminnayeri M (2018) Optimizing the number of outbound doors in the cross-dock based on a new queuing system with the assumption of beta arrival time. Scientia Iranica 25(4):2282–2296. https://doi.org/10.24200/sci.2017.4452

Munoz F and Lee S (2021) A stochastic model to determine the required number of trucks in sugarcane harvest systems. In G. A., K. K., and P. K. (eds) IISE Annual Conference and Expo 2021 (pp 704–709). Institute of Industrial and Systems Engineers, IISE

Nazzal D (2011) A closed queueing network approach to analyzing multi-vehicle material handling systems. IIE Trans (institute of Industrial Engineers) 43(10):721–738. https://doi.org/10.1080/0740817X.2011.566907

Otten S, Krenzler R, Xie L, Daduna H, Kruse K (2021) Analysis of semi-open queueing networks using lost customers approximation with an application to robotic mobile fulfilment systems. Or Spectrum. https://doi.org/10.1007/s00291-021-00662-9

Pourvaziri H, Pierreval H, Marian H (2021) Integrating facility layout design and aisle structure in manufacturing systems: Formulation and exact solution. Eur J Oper Res 290(2):499–513. https://doi.org/10.1016/j.ejor.2020.08.012

Rajagopalan S, Heragu SS (1997) Advances in discrete material handling system design. Sadhana 22(2):281–292. https://doi.org/10.1007/BF02744493

Raman D, Nagalingam SV, Gurd BW, Lin GCI (2009) Quantity of material handling equipment—a queuing theory based approach. Robot Comput-Integrat Manuf 25(2):348–357

Raman D (2011) Integrated optimisation of facilities layout and material handling system. In: IEEE International Conference on Industrial Engineering and Engineering Management, IEEM2011, 758–762. https://doi.org/10.1109/IEEM.2011.6118018

Roy D, de Koster R (2018) Stochastic modeling of unloading and loading operations at a container terminal using automated lifting vehicles. Eur J Oper Res 266(3):895–910. https://doi.org/10.1016/j.ejor.2017.10.031

Roy D, Krishnamurthy A, Heragu SS, Malmborg CJ (2012) Performance analysis and design trade-offs in warehouses with autonomous vehicle technology. IIE Trans (institute of Industrial Engineers) 44(12):1045–1060. https://doi.org/10.1080/0740817X.2012.665201

Roy D, Krishnamurthy A, Heragu SS, Malmborg CJ (2014) Blocking effects in warehouse systems with autonomous vehicles. IEEE Trans Autom Sci Eng 11(2):439–451. https://doi.org/10.1109/TASE.2013.2243910

Roy D, Krishnamurthy A, Heragu S, Malmborg C (2015a) Queuing models to analyze dwell-point and cross-aisle location in autonomous vehicle-based warehouse systems. Eur J Oper Res 242(1):72–87. https://doi.org/10.1016/j.ejor.2014.09.040

Roy D, Krishnamurthy A, Heragu S, Malmborg C (2015b) Stochastic models for unit-load operations in warehouse systems with autonomous vehicles. Ann Oper Res 231(1):129–155. https://doi.org/10.1007/s10479-014-1665-8

Roy D and de Koster R (2020) Optimal stack layout configurations at automated container terminals using queuing network models. In: Operations Research/ Computer Science Interfaces Series (pp 437–461). Springer. https://doi.org/10.1007/978-3-030-39990-0_19

Sahu AK, Sahu AK, Sahu NK (2017) Appraisements of material handling system in context of fiscal and environment extent: a comparative grey statistical analysis. Int J Logist Manag 28(1):2–28. https://doi.org/10.1108/IJLM-09-2015-0163

Schleyer M, Gue K (2012) Throughput time distribution analysis for a one-block warehouse. Transp Res Part E 48(3):652–666. https://doi.org/10.1016/j.tre.2011.10.010

Sembakutti D, Kumral M, Sasmito AP (2017) Analysing equipment allocation through queuing theory and Monte-Carlo simulations in surface mining operations. Int J Min Mineral Eng 8(1):56–69. https://doi.org/10.1504/IJMME.2017.082693

Seyedhoseini SM, Rashid R, Teimoury E (2015) Developing a cross-docking network design model under uncertain environment. J Ind Eng Int 11(2):225–236. https://doi.org/10.1007/s40092-014-0088-0

Shen Y, Xu X, Zou B, Wang H (2021) Operating policies in multi-warehouse drone delivery systems. Int J Prod Res 59(7):2140–2156

Smith J (2016) Joint optimisation of buffers and network population for closed finite queueing systems. Int J Prod Res 54(17):5111–5135. https://doi.org/10.1080/00207543.2016.1154213

Smith JMG, Barnes R (2015) Optimal server allocation in closed finite queueing networks. Flex Serv Manuf J 27(1):58–85. https://doi.org/10.1007/s10696-014-9202-2

Smith JM, Kerbache L (2012) State-dependent models of material handling systems in closed queueing networks. Int J Prod Res 50(2):461–484. https://doi.org/10.1080/00207543.2010.535041

Smith JMG (2013) Queueing network models of material handling and transportation systems. In: Handbook of Stochastic Models and Analysis of Manufacturing System Operations (pp 249–285). Springer

Smith JMG (2018) Transportation and loss queues G(E). In: Springer Series in Operations Research and Financial Engineering (pp 133–180). Springer Nature. https://doi.org/10.1007/978-3-319-78822-7_4

Smith JM, Cruz FRB and van Woensel T (2008) Optimal server allocation in general, finite, multi-server queueing networks, manuscript. Ftp://Ftp.Est.Ufmg.Br/Pub/Fcruz/PubliCs/Cap.Pdf

Soufi Z, David P, Yahouni Z (2021) A methodology for the selection of Material Handling Equipment in manufacturing systems. IFAC-PapersOnLine 54(1):122–127. https://doi.org/10.1016/j.ifacol.2021.08.193

Stephens MP (2020) Material handling equipment. Manufacturing facilities design and material handling, 229–302. https://doi.org/10.2307/j.ctv15wxptd.14

Sukhotu V, Peters BA (2012) Modelling of material handling systems for facility design in manufacturing environments with job-specific routing. Int J Prod Res 50(24):7285–7302. https://doi.org/10.1080/00207543.2011.645512

Tappia E, Roy D, De Koster R, Melacini M (2017) Modeling, analysis, and design insights for shuttle-based compact storage systems. Transp Sci 51(1):269–295. https://doi.org/10.1287/trsc.2016.0699

Tappia E, Roy D, Melacini M, De Koster R (2019) Integrated storage-order picking systems: technology, performance models, and design insights. Eur J Oper Res 274(3):947–965. https://doi.org/10.1016/j.ejor.2018.10.048

Tompkins JA, White JA, Bozer YA, Tanchoco JMA (2010) Facilities planning. John Wiley and Sons

Tu Y-M, Chang C-H (2014) Giga-fab scale determination model for wafer fabrication based on production performances. World Congress Eng 2:1040–1044

Tu Y-M, Lu C-W, Lee AHI (2013) AMHS capacity determination model for wafer fabrication based on production performance optimization. Int J Prod Res 51(18):5520–5535. https://doi.org/10.1080/00207543.2013.784416

Wang W, Wu Y, Qi J and Wang Y (2020) Design and performance analysis of robot shuttle system. In: 2020 International Conference on Artificial Intelligence and Electromechanical Automation, AIEA 2020, 255–259. https://doi.org/10.1109/AIEA51086.2020.00061

Xi S, Chen Q, Mao N, Li X, Yu A (2017a) Buffer allocation problem of assembly manufacturing system with bulk storage and transportation. Jisuanji Jicheng Zhizao Xitong 23(12):2657–2664. https://doi.org/10.13196/j.cims.2017.12.011

Xi S, Chen Q, Mao N, Yu A (2017b) Modeling and analysis of assembly manufacturing system with bulk storage and transportation. Jisuanji Jicheng Zhizao Xitong 23(1):32–43. https://doi.org/10.13196/j.cims.2017.01.005

Xu Y, Chen Q, Mao N (2016) System performance analysis of flexible flow shop with material handling unit. Jisuanji Jicheng Zhizao Xitong 22(3):764–773. https://doi.org/10.13196/j.cims.2016.03.020

Yang P, Jin G, Duan G (2021) Modelling and analysis for multi-deep compact robotic mobile fulfilment system. Int J Prod Res. https://doi.org/10.1080/00207543.2021.1936264

Yuan Z, Gong Y (2016) Improving the speed delivery for robotic warehouses. IFAC-PapersOnLine 49(12):1164–1168. https://doi.org/10.1016/j.ifacol.2016.07.661

Zeng Q-C, Zhang X-J, Zhang Q (2016) Optimization model of terminal container truck appointment based on coordinated service of inner and outer container trucks. Jiaotong Yunshu Gongcheng Xuebao 16(1):115–122

Zhang X, Zeng Q, Wang Z (2019) Modeling the closed queueing network of truck allocation optimization in container terminals. Xitong Gongcheng Lilun Yu Shijian 39(2):409–417. https://doi.org/10.12011/1000-6788-2017-1163-09

Zhang H-Y, Xi S-H, Chen Q-X, Smith JM, Mao N, Li X (2021) Performance analysis of a flexible flow shop with random and state-dependent batch transport. Int J Prod Res 59(4):982–1002. https://doi.org/10.1080/00207543.2020.1712488

Zhou B-H, Chen J-X (2013) Queuing-based performance analytical model for continuous flow transporters of AMHS. J Donghua Univ (English Edition) 30(2):90–95

Zhou B-H, Chen J-X, Zhao M (2015) Performance analysis for continuous flow transporters of Interbay AMHS with priority rules. Zhejiang Daxue Xuebao (gongxue Ban) 49(2):296–302. https://doi.org/10.3785/j.issn.1008-973X.2015.02.015. (**314**)

Zhou B-H, Chen J-X, Lu Z-Q (2016) An analytical model for continuous flow transporters of AMHSs with multi-loop conveyors and priority rules. Int J Comput Integr Manuf 29(5):489–503. https://doi.org/10.1080/0951192X.2015.1070204

Zhu D-J, Wu L-H (2014) Queueing network-based performance model for wafer fabrication automated material handling system. Jisuanji Jicheng Zhizao Xitong 20(9):2267–2274. https://doi.org/10.13196/j.cims.2014.09.023

Zou B, Xu X, Gong YY, De Koster R (2018) Evaluating battery charging and swapping strategies in a robotic mobile fulfillment system. Eur J Oper Res 267(2):733–753. https://doi.org/10.1016/j.ejor.2017.12.008

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