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HEALTHCARE SUPPLY CHAINS

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1. What is a healthcare supply chain?

In his widely recognized and cited book, Christopher (2016) defines a supply chain (SC) (Refer to Table 1 for a complete list of acronyms used in the chapter) as a "network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer" (p.13). The author defines supply chain management (SCM) as the "management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole" (p.3). It is clear from these definitions that every SC is a system of organizations, materials, resources (including human capital), activities, information, and finances that help move a product or service from suppliers to end customers/ consumers while optimizing end-to-end efficiency and effectiveness. As a result, to match customer requirements with supply constraints, SCM as a management strategy is characterized by a *systems approach* (i.e., considers the organizations in the SC as an end-to-end, integrated entity), a *strategic orientation* (i.e., aligns the intra- and inter-firm goals and capabilities with those of the SC), and a *customer focus* (i.e., focuses on customer value as the key driver of the SC's activities) (Mentzer *et al.* 2001).

Table 1: List of acronyms.

Acronym	Description	Acronym	Description
ACO	Accountable care organization	IoT	Internet of things
ACT	Artemesinin combination therapy	IT	Information technology
AI	Artificial intelligence	NGO	Non-governmental organization
CAF	Contract administration fee	NHS	National Health Service
CRO	Contract research organization	NIHR	National Institute for Health Research
Cryo	Cryoprecipitate	LOS	Length of stay
CT	Computed tomography	MRI	Magnetic resonance imaging
DRG	Diagnosis-related group	OECD	Organization for economic co-operation and development
DTOC	Delayed transfer of care		
ED	Emergency department	OEM	Original equipment manufacturer
FDA	Food and Drug Administration	OM	Operations management
FFS	Fee-for-service	OR	Operating room
GDP	Gross domestic product	PA	Physician associate
GFT	Google Flu Trends	PBM	Pharmacy benefit manager
GP	General practitioner	R&D	Research and development
GPO	Group purchasing organization	RBB	Regional blood banks
hSC / hSCM	Healthcare supply chain / Healthcare supply chain management	SC / SCM	Supply chain / Supply chain management
ICU	Intensive care unit	VRBPAC	Vaccines and related biological products advisory committee

This definition of SCM can easily be extended to healthcare supply chains (hSCs). hSCM is the management of people (such as patients, providers, purchasers, and payers), processes, information, and finances to deliver medical products (pharmaceuticals, medical devices, and health aids) and services (curative, preventive, rehabilitative, and palliative care) to consumers and to enable the flow of patients in the care system, all in the pursuit of enhancing clinical outcomes and user experience, while controlling costs (de Vries and Huijsman 2011).

In recent years, the world's population has been increasing and aging (Table 2). Consequently, countries are spending a significant portion of their gross domestic product (GDP) on healthcare (e.g., 9.2% and 17.2% in 2017 for the UK and the US, respectively) (OECD 2017). There are significant and well-documented inefficiencies in healthcare delivery, leading to wastes. Therefore, the need to contain costs while ensuring quality care is evident. Improved SCM lends itself as an opportunity to deliver effective and affordable healthcare.

Table 2: The global population and average life expectancy over time.

Year	Global population	Average life expectancy	% of population aged 65 and over
1900	1.6 billion	32 years	
1950	2.5 billion	48 years	
2015	7.3 billion	68.6 years	8.5%
2050	9.4 billion (projected)	76.2 years (projected)	17% (projected)

Sources: Tables 2-1 and 4-2 of He *et al.* (2016), Table 1.3 of Livi-Bacci (2001), and Table 1 of Riley (2005).

The remainder of the chapter is organized as follows. In accordance to the classification of Betcheva *et al.* (2019), we categorize hSCs into six main categories and discuss the key strategies, challenges, and risks as well as the existing research for each category. For each hSC, we provide at least one efficient and effective SC strategy that has been used in practice. We close each section with a short discussion on future research. The chapter ends with several concluding remarks. Two caveats are worth mentioning. Due to our familiarity with the healthcare systems in the US and the UK, our descriptions of hSCs are predominantly based on the context of these two countries. Also, there exists a large body of Operations Management (OM) literature in the realm of healthcare. For the sake of brevity, we discuss only a selected few academic papers for each SC.

2. Health services SCs

2.1. Medical SCs. Medical care provision takes place across primary, secondary, and tertiary care. Primary care refers to the first healthcare point of contact for patients (e.g., general practitioners (GPs), pharmacists). Secondary care encompasses hospital, clinic, or community care (e.g., planned operations, emergency care), while tertiary care refers to highly specialized treatment (e.g., neurosurgery). Patients flow across primary, secondary, and tertiary care in several ways. We note that patient flows can refer to either patient "pathways" or patient "journeys" and, it is important to distinguish between the two. Patient or clinical pathways are standardized plans of care for patients with a particular diagnosis. Patient journeys refer to how patients proceed through healthcare systems; Trebble *et al.* (2010) outline how to employ process mapping to capture and examine a patient journey.

At a high level, the typical patient flow begins with patients first visiting their GP. Aside from GPs, other primary care providers include pharmacies, optometry, and dental services. After consulting with a primary care provider, patients can subsequently be referred to a hospital. Patients visiting hospital outpatient clinics do not require a bed, and thus differ from inpatients who are admitted to a hospital. Patients who have a pre-arranged date to stay in a hospital are elective admissions. Alternatively, patients can also present to a hospital's emergency department (ED), via ambulance or walk-in, as non-elective patients. After being seen by a healthcare provider, ED patients are either discharged (to go home, to community care, etc.) or admitted to the hospital. Inpatients may require surgery in operating rooms (ORs), may need to stay in intensive care units (ICUs), or need further treatment and rehabilitation in various wards.

Figure 1 depicts a broad and simplified version of typical patient flow for a patient episode, which is typically initiated by a referral or admission and is ended by a discharge. Several remarks are in order for Figure 1. First, within the hospital, different patients visit different departments, and within one admission stay, a patient may switch between wards multiple times. Secondly, one can identify various flows *within* each department. For example, when a patient visits the ED, they are first triaged by medical staff (often a nurse). The patient may then undergo medical tests, receive physician consultations and be administered medications and treatments. Finally, the patient is discharged or admitted. Thirdly, patients can also be transferred from one hospital to another.

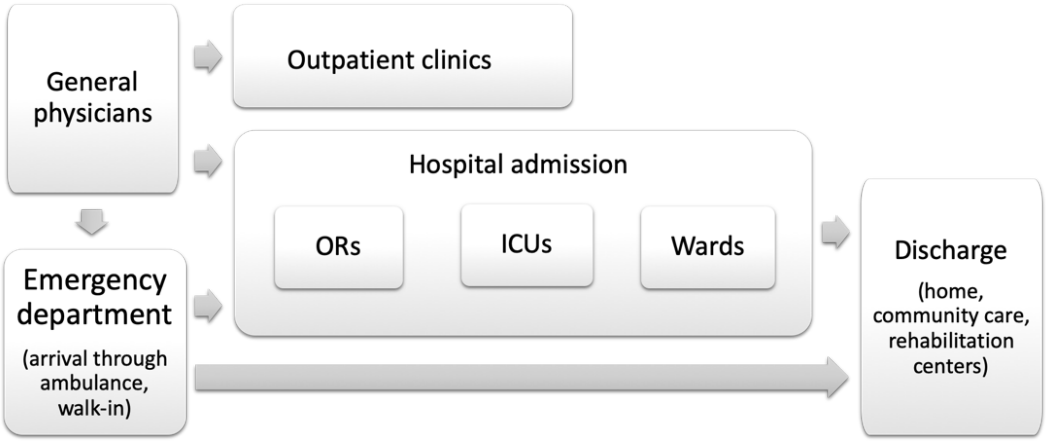

Figure 1: A simplified and broad overview of the medical SC.

Unlike commercial SCs, patients rather than materials or products flow through different stages of this hSC, within and across care facilities. Therefore, a critically important task is to accurately move patients between stages in a timely and efficient manner. Otherwise, patient safety, health outcomes, and experience can become compromised, and resources may be wasted. System coordination plays a vital role in hospital operations. Bretthauer *et al.* (2011) show that one of the key reasons for poor performance at EDs is bed blocking (in which patients, who need to be admitted, occupy limited ED beds due to bed unavailability in wards). A further instance of bed blocking, or delayed transfer of care (DTOC), occurs when (mainly elderly) patients stay in hospital for excessive periods of time due to the lack of spaces in community care. Another difficult task is patient routing within hospitals. In some cases, patients are routed to non-preferred wards because of bed shortages in preferred wards. These outlier patients may need to be transferred to appropriate wards at a later point in time. Stylianou *et al.* (2017) report that 10% of admitted patients are outliers. DTOC and outlier transfers may result in patients receiving delayed treatment and an increase in patients' length of stay (LOS), which also has economic ramifications. Freeman *et al.* (2018) show that quality of care is improved if departmental routing is consistent; i.e., if the same types of patients are served in the same department, and that consistent referral is particularly beneficial for the most complex patients (emergency patients with multiple comorbidities).

Lu and Lu (2018) empirically study the inter-hospital patient routing decisions for the case of patients suffering from acute myocardial infarction. Heart attack patients are often transferred from the ED of one hospital to the ED of another. One reason for this is that some acute care hospitals lack the resources to provide timely revascularization procedures. The researchers uncover the determinants of transfer destinations. By focusing on the sending and receiving hospital, they show that the hospital relationship (when the two hospitals are affiliated with the same hospital system) plays a larger role than the distance between the two hospitals, as well as the quality (based on publicly available measures) of the receiving hospital. Alarmingly, it is also demonstrated that relationship-based transfers are associated with significantly higher patient readmission rates (measured by 30-day readmission rates of transferred patients) than distance-based and quality-based transfers. These results have strong implications, especially in the face of policy initiatives to reduce readmission rates.

Wang *et al.* (2018) examine how scheduling can be improved between two service providers involved in pre-operative care who often reside in separate clinics (the anesthesiology preoperative clinic and the internal medicine clinic in their case). Typically, patients have to coordinate their trips across multiple physicians. This can result in long delays for patients to, and between, services. Also, as an outcome of referrals, providers experience a high variance in their daily operations. The authors propose a coordinated scheduling policy that takes into account system profit from both services, patient waiting time and clinic overtime.

Inefficiencies such as DTOC and patient outliers illustrate that patient SCs are prone to fragmentation. Care fragmentation threatens health outcomes, patient experience, and continuity of care. To overcome the lack of coordination between providers and ensure timely and appropriate patient flow, new care models such as integrated care initiatives are receiving growing attention. We refer the reader to NHS Improvement (2017) for a series of case studies describing various initiatives UK trusts have undertaken to improve patient flow. Researchers should,

therefore, direct their efforts in analyzing what these models mean for system capacity, scheduling, and patient routing decisions from an SCM perspective. There is a wealth of OM literature regarding scheduling carrying implications for individual hospitals. Expanding this research in a multi-hospital context or across stakeholders (e.g., capacity management between hospitals and nursing homes) has the potential to simultaneously build on hSC research and address fragmentation in healthcare.

2.2. Community and social care SCs. The provision of community care occurs in residential settings (such as patient's homes, community centers, and schools) (Charles 2019). Community care captures a diverse set of services ranging from adult care (e.g., district nursing and palliative care), therapy services (e.g., physiotherapy, occupational therapy, and speech and language therapy), preventative services (e.g., sexual health and smoking cessation clinics), and health promotion services (e.g., school nursing and health visiting) to specialist services such as offender healthcare (Charles 2019). In England, community care accounts for £1 in every £10 spent by healthcare commissioners, with distinct nursing, health visiting, and midwifery care accounting for the largest cost (Gershlick and Firth 2017). Providers include the NHS, general practice, private providers, local authorities, charities, social enterprises, and community interest companies (Gershlick and Firth 2017). Community care services offer care and support for patients with long-term conditions and complex health needs and play a role in assisting individuals to live independently in their homes (Charles 2019). Community care workers coordinate care with other health services, such as GPs and hospitals, and social care providers. With an increase in the prevalence of chronic diseases, demand for community care is likely to rise. However, a growing shortage in key parts of the workforce will make it difficult to meet demand (Charles 2019). For instance, between 2010 and 2018 the total number of NHS nurses working in community health services fell by 14% while the number working in acute adult health increased by 9% (Charles 2019). Reinforcing community-based care is particularly important, especially in the face of a growing focus to bring care closer to patients' home as well as to relieve pressure from other parts of the healthcare system (NHS England 2013).

Social care is the provision of care and support to individuals requiring assistance in daily activities such as cooking, cleaning, and personal hygiene. These needs arise due to age, illness, physical disability, or mental health. A report published by the Institute for Fiscal Studies states that in the UK, the number of people aged 65 and over is growing three times faster than the number of people aged under 65 (Charlesworth and Johnson 2018). There is also a rising burden of disease as more individuals are living with a chronic disease and many are affected by more than one condition. The report also highlights an increasing trend of younger adults who live with a disability. As life expectancy increases, the cost of care for disabled persons is rising. Social care for people of working age is now costing public bodies about as much as that for older people (NHS Digital (2017) cited in Bottery *et al.* (2018)).

A representative social care SC based on the UK system is shown in Figure 2. In England, local authorities are responsible for public funds directed to social care services and the commissioning of care. Eligibility depends on both needs and financial means assessment (Bottery *et al.* 2018). Unlike public spending on health, expenditure on social care has been falling since 2009-2010

(Charlesworth and Johnson 2018). Currently, a large portion of care is privately paid for with no cap on the amount that individuals have to pay out-of-pocket (The King's Fund 2018).

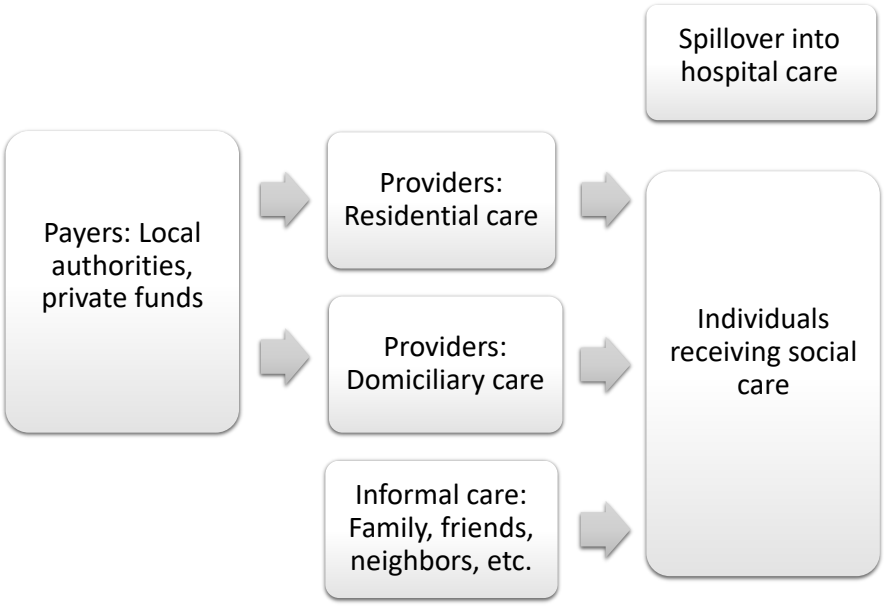

Figure 2: A representative social care SC in the UK context.

Providers of social care consist of private, for-profit, or non-profit entities, providing residential care or domiciliary care (i.e., care at individuals' homes). These organizations include residential care homes, nursing homes, and specialist colleges providing personal care and accommodation (The King's Fund 2018). Perhaps surprisingly, the workforce involved in social care is larger than that of the NHS's (Charlesworth and Johnson 2018). The sector faces high turnover rates and it is projected that there will be an increased need for staff to meet the rising demand for social care (Bottery *et al.* 2018, The King's Fund 2018). Relatives, friends, and neighbors also provide a large portion of care, termed informal care. This often results in carers having to partially, or entirely, leave the labor force.

There has been a decrease in publicly-accessed social care in the UK since 2009 and it is speculated that this has put a greater strain on informal care (Charlesworth and Johnson 2018). Additionally, individuals with unmet social needs may be ending up in hospitals or relying more heavily on GPs. A portion of DTOC can be attributed to social care as awaiting a home care package is still the number one reason for delayed hospital discharge (Bottery *et al.* 2018). Another key challenge brought about by public budget cuts is that it has become more expensive for individuals who privately pay for services as providers have engaged in cross-subsidization between rates charged to publicly- and privately-funded individuals (Charlesworth and Johnson 2018).

Robertson *et al.* (2014) provide a comparison of social care in nine different OECD countries. Similar to England, Australia provides government funding based on mean and needs (with

informal care factored into the assessment). Countries like France and Germany have mandatory long-term care insurance. Notably, France also has a fairly large private insurance market, which is unlike in the UK where few private insurance products exist. Although Medicaid provides coverage for low-income individuals in the US, the majority of social care is privately paid for. Across countries, there are differences in the proportion of for-profit, non-profit, and publicly run providers.

Technology has changed and continues to change the way healthcare and social care organizations operate. Lu *et al.* (2018) empirically investigate the effect of information technology (IT) adoption on staffing and resident admissions in US nursing homes. In this industry, there is high competition across providers, payment is both private and public, and quality is mainly determined by nurse staffing policies. The authors show that automation leads to an increase in staffing levels in low-end nursing homes as it makes care providers more productive (a complementary effect). On the other hand, nurse staffing levels decrease after automation in high-end homes. This is because technology may serve as a substitute for labor since the marginal benefit of providing additional quality (in a high-end nursing home) is relatively low. Notably, it is shown that increased automation decreases admissions of less profitable residents (those paid for by Medicaid).

As the population grows and ages, there is an increasing demand for social care as well as healthcare. Care models that integrate social and healthcare provision play a key role in ensuring patient centricity and the holistic management of patient needs (National Collaboration for Integrated Care and Support 2013). Thus, future research should examine the interaction between the two sectors. There has also been a push towards bringing care as close to patients' homes as possible. A 2013 report by the NHS England outlines the elements required to transform urgent and emergency care services in England and bring care closer to patients' homes (NHS England 2013). The report highlights the fact that improving technologies allow for the management of many problems in a patients' home or local community that would have required hospital admission in previous years. The report also advocates for the support and promotion of self-care by the NHS. Individuals, especially those with long-term conditions, can become experts in their problems. With the proper information and advice (e.g., through accessible and reliable telephone services), patients can become capable of managing many problems themselves or with the help of friends and family. Shifting care from hospitals and into patients' homes have the potential to improve the quality of care (e.g., eliminate the risk of hospital infections), patient experience and comfort, as well as reduce costs. The Buurtzorg model of care or "neighborhood care" emerged and operates in the Netherlands. Under this model, nurse teams are responsible for a few dozen patients in a particular area. Nurses act as health coaches for patients and their families by offering advice and advocating preventative care. In addition, nurses also provide some care themselves or elicit the services of other providers (Brindle 2017). A brief by the Royal College of Nursing discusses the success of this community care program as well as how it may be adapted to a UK context (Royal College of Nursing 2016).

2.3. Workforce SCs. Healthcare staff such as doctors, nurses, and therapists are arguably the single most important asset to hSCs (Figure 3). Jointly with social care, jobs in the healthcare sector account for over 10% of total employment in many OECD countries (OECD 2016). The

NHS in England employs over a million people. However, it has been reported that there is a current shortfall of 100,000 staff and this may take a toll on waiting lists, patient care, and staff experience (Beech *et al.* 2019). This also seems to be the case for social care with 1 in 10 social workers roles vacant (The Health Foundation *et al.* 2018). Beech *et al.* (2019) warn that there should be collaborative workforce planning between the two sectors, as the NHS can have significant "gravitational pull" on social care staff.

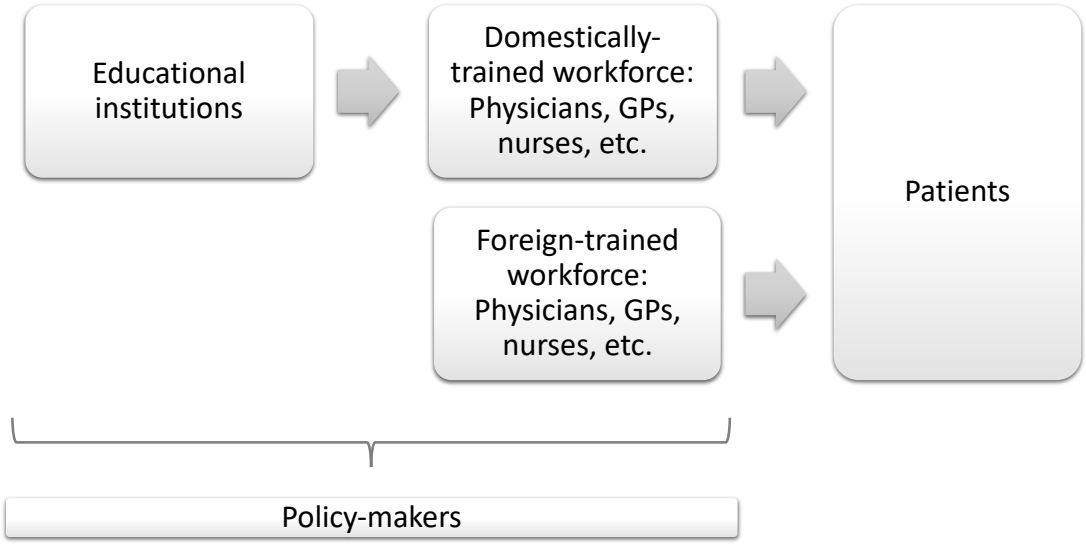

Figure 3: A representative workforce SC.

The supply of clinical workforce depends on the inflow of trained doctors and nurses and the retention of professionals. One lever commonly employed by countries' governments is the adjustment of annual quotas for the admission of students into medical educational institutions. Two challenges to the training of clinical personnel are recruitment and attrition. Although the total number of doctors has increased across OECD countries, the share of GPs has fallen and only about a third of doctors are generalists (OECD 2016). Some countries have addressed this by increasing the number of post-graduate training places for general medicine. With growing recognition on the importance of primary care in treating an aging population with chronic conditions, policy-makers and healthcare institutions need to consider how to ensure a greater supply of GPs. Attrition is also a key concern to the inflow of healthcare human capital. Almost a quarter of UK nursing students, due to complete their training in 2017, abandoned or suspended their studies (Buchan *et al.* 2019), introducing a variety of problems and wasted resources. Another source of workforce inflow into a domestic healthcare sector is the migration of foreign-trained workers. An inflow of human capital for one country represents an outflow for another. It has been argued that reliance on foreign-trained workers "free-rides" on the training efforts of other countries and can worsen shortages of skilled medical workers in those countries (OECD 2016).

The workforce has been changing and new healthcare roles have emerged as part of innovative workforce SC strategies. Physician associates (PAs), medically trained generalists who work

under the supervision of doctors, have patient lists and perform diagnostic and therapeutic procedures. However, they have a limited scope of practice (e.g., unable to prescribe or request x-rays or computed tomography (CT) scans) (NHS England 2019). The role appeared in the US fifty years ago and, currently, there are 100,000 Pas who work in both primary and secondary care in the country. In comparison, there are 350 practicing Pas and another 550 in training in the NHS (NHS England 2019). A study conducted by the NIHR has demonstrated the impact of Pas in hospitals (National Institute for Health Research 2019). It was shown that Pas support the workloads of clinical teams and contribute to team continuity (e.g., by inducting new junior doctors). This allows doctors to tend to more complex patients and attend training. In addition, PAs were found to positively impact patient flow and experience. To ensure patient continuity of care and to alleviate the GP shortage in primary care, the Department of Health and Health Education England has expressed an interest in the recruitment of more Pas into primary care (NHS England 2019).

Roles are not only arising, but traditional job boundaries are gradually blurring as workers perform more and more tasks formerly executed solely by professionals higher up in the healthcare hierarchy (Oxtoby 2009). “Pharmacists are screening, nurses are prescribing, GPs are specializing, and consultants are increasingly taking on managerial roles” (Oxtoby 2009). Blouin and Adams (2017) discuss the role pharmacists play in healthcare *delivery* (in assuring appropriate medication therapy management), healthcare *access* (by providing a variety of services as one of the most accessible health professionals), and *public health* (such as facilitating appropriate prescription opioid use, providing increased access to immunizations, and contributing to disaster response by administering medication, education and care for individuals).

Taken together, it is clear that the dynamics (e.g., the types and number of workers) of the workforce inflow are evolving. Policies regarding pension and retirement age as well as measures enacted to retain professionals (for instance, changing working conditions) alter the outflow of healthcare workers. Also, policy-makers can influence the geographic distribution of medical workers. In certain countries like Canada, there is a significant shortage of doctors in rural areas. OECD (2016) outlines various ways in which this may be addressed including financial incentives, the use of telemedicine, regulations (e.g., restrictions to set up practice in adequately supplied areas) and competency transfer from doctors to nurses. It is also important to note that non-clinical staff (such as receptionists, accountants, IT specialists, etc.) also constitute a portion of the healthcare workforce.

The government can influence the operations and performance of hSCs through the policies it enacts. Lu and Lu (2017) empirically examine nurse-staffing practices in the US following laws prohibiting mandatory overtime. Employing difference-in-difference analysis on a database capturing more than 90% of US nursing homes in 2004-2012, the authors show that such laws are associated with a reduction in service quality (measured by deficiency citations on quality indicators). The authors reason that this is due to two unfavorable changes in the composition of nurse-staffing (decreased hours of permanent nurses and increased hours of contract nurses). Whereas understaffing leads to low-quality service, overstaffing leads to idleness and high costs. The researchers put forward that in the event of understaffing; nursing homes can employ two levers–hire contract nurses or have permanent nurses work overtime. They posit that the effect

of the mandatory laws limits managers' ability to employ the latter lever (decreasing the overtime limit a nurse can work).

The management of the inflow and outflow of healthcare workers underlies SCM of the healthcare workforce. Currently, there is a severe shortage of human resources in healthcare with an estimated 17.4 million healthcare workers missing from the global medical sector (The Medical Futurist 2018). The aging and burn-out of physicians, in combination with the rising demand from an aging population increasingly suffering from chronic diseases, are expected to further exacerbate the shortfall (The Medical Futurist 2018). Attracting and retaining health workers is dependent upon the reimbursement providers receive for their services. Therefore, provider incentives arising from new reimbursement schemes need to be carefully evaluated. Researchers and regulators should also scrutinize newly proposed regulations and policies. With rising healthcare costs, there has been an emphasis on cost reduction. This has put pressure on healthcare personnel to do more with less. We caution that SC improvements should focus on system-wide changes rather than simply increasing expectations from the workforce. The human resource crisis may lead to opportunities for process optimization in healthcare. In addition, as in many other sectors, technological advancements are influencing the healthcare workforce. Technologies such as artificial intelligence (AI) and telemedicine may help ease the burden on healthcare providers. For instance, AI may facilitate more accurate diagnosis, assist in decision making, and execute repetitive or bureaucratic tasks so that clinicians can concentrate their efforts on value-adding activities (The Medical Futurist 2018). Although wider adoption of health technologies has the potential to ameliorate the human resource shortage, many questions arise regarding the ethics, implementation, and feasibility in applying various technological advancements in healthcare delivery. Further exploration is required concerning the opportunities and challenges of new technologies to health providers.

2.4. Reimbursement SCs. Financing is an important part of healthcare services and the reimbursement of healthcare providers has been, and continues to be, a subject of debate and research interest. Different countries have different reimbursement systems. Some countries, like England, have a universal healthcare system in which residents have free access to healthcare, which is paid for by government general taxation. In the US, Medicare and Medicaid are federal and state programs, which offer coverage to elderly and low-income individuals, respectively. The remaining population is either privately insured or uninsured. Many countries employ hybrid systems in which payers may be central and local governments, insurance companies, employers, charity organizations, relatives and patients themselves. Patients receive healthcare services from providers (such as hospitals, clinics, and physicians), who are accordingly reimbursed by payers. Many different reimbursement schemes have been evaluated in the literature. These range from block contracts and fee-for-service (FFS) payments, which have been used in the past, to recently introduced diagnosis-related group (DRG)-based and/or performance-based prospective payment schemes based on bundles, outcomes, and values. Jiang *et al.* (2012) review some of these popular contracts. It is worthwhile to note that capitation has recently regained attention because this payment scheme facilitates the reimbursement of integrated care (e.g., accountable care organizations (ACOs)) without the use of complicated and segmented contracts.

Adida and Bravo (2019) explore the issue of coordinating referral services in a business-to-business context. Specifically, the authors examine the interaction between managing organizations (such as ACOs and health maintenance organizations) and third-party providers (e.g., specialists). Managing organizations (requesters) refer patients to providers when advanced care is needed and are financially responsible for the care patients receive. However, requesters can exert effort in preventive care to reduce the volume of patients referred. Similarly, providers can exert effort in non-billable activities (such as patient education), which reduces the possibility of patients requiring further costly interventions. The authors formulate a contracting problem between the requestor and the provider, which maximizes joint profits and introduce a penalty contract that penalizes providers for treatment failures. It is demonstrated that social welfare (a system comprising of the requestor, provider and patients*)* is improved under a penalty contract relative to an FFS contract.

Calsyn and Lee (2012) discuss alternatives to FFS payments in healthcare and present several case studies outlining recent reform projects in the US. For example, in 2002, The Centers for Medicare and Medicaid Services implemented the hospital readmissions reduction program which lowers payments to hospitals with excess 30-day readmissions**.** The program supports the national goal of improving healthcare for Americans by linking payments to the quality of hospital care (Joynt *et al.* 2016).

As new care models become increasingly focused on system coordination and integration, reimbursement is fundamental in ensuring cooperative behavior. Furthermore, there is a need to ensure the seamless transition of reimbursement schemes theoretically proposed in literature into practice.

2.5. Medical equipment SCs. The sophistication and cost of medical equipment, and consequently its maintenance, continue to escalate. For one such device, magnetic resonance imaging (MRI), lifetime maintenance costs can easily approach the original purchase price (Chan *et al.* 2019). Medical equipment is vital for the prevention, diagnosis, and treatment of disease as well as patient rehabilitation (World Health Organization 2011). An equipment breakdown can have substantial consequences such as risk of injury or death to the user or the patient, inappropriate therapy or misdiagnosis (World Health Organization 2011). Therefore, equipment must be properly maintained to ensure its safety and reliability. In addition, equipment failures impact equipment availability which, in turn, can adversely affect care quality, patient wait times (Cruz and Rincon 2012), and hospital financials. Maintenance and repair of medical equipment require financial, physical (e.g., testing and calibration tools), and human resources. Maintenance services can be preventative (which seek to reduce the failure rate of equipment) or corrective (which restore the function of equipment that has already failed) and various services can be executed in-house, by the original equipment manufacturer (OEM) or by a third-party provider (World Health Organization 2011).

With an external maintenance provider, value is co-produced (Karmarkar and Roels 2015) as operational performance depends on both the operator handling of the equipment as well as maintenance effort of the part of the provider. Recently, Chan *et al.* (2019) empirically examine the two contract types for the provision of maintenance services of medical imaging devices.

Using sales and service data on 712 CT and MRI scans sold to 441 hospitals by a large OEM in a major OECD country, the authors find that moving from a basic pay-per-service plan to a fixed-fee, full protection plan reduces reliability (increases failure rate by 33%) and increases service costs. The authors caution against the prevailing view that providers should assume more equipment failure risk. It is suggested that this may lead to incentive effects that lower the operator's level of care. Chan *et al.* (2019) show that although both contract schemes are used in practice, a pay-per-service plan significantly improves operational performance metrics over a fixed-price full-protection plan.

The operational performance of medical equipment (e.g., the failure rate) is largely determined by the client's decisions such as the training of operators (Jain *et al.* 2013). This is particularly evident in developing countries where the overarching reliance on external vendors for maintenance services (Cruz and Rincon 2012) and out-of-service equipment (Malkin and Whittle 2014) is attributed to the absence of properly trained staff. Malkin and Whittle (2014) examine a program offered by Engineering World Health which served to train biomedical technicians in Rwanda. The researchers demonstrate that nearly twice as much equipment was out-of-service at hospitals where technicians had not been trained, compared to hospitals where technicians had completed one year of training. Operators may also lack the material resources to handle maintenance activities on their own. It has been reported that OEMs deny other organizations access to documentation and products such as online diagnostics programs to create barriers to competition (Blumberg 2004). This suggests that more collaborative arrangements between manufacturers and operators as well as greater support offered by OEMs have the potential to improve the operational performance of equipment. We, thus, encourage researchers to examine how more value can be achieved in medical equipment SCs in developing countries.

3. Pharmaceutical SCs

3.1. Innovation and R&D SCs. Drug discovery and development is a long and costly process which can take, on average, 10 to 15 years and cost $2.6 billion (PhRMA 2016). To gain regulatory (i.e., Food and Drug Administration (FDA) in the US) approval, potential medicines move through pre-clinical testing and several phases of clinical trials. Human testing commences at phase 0 where pharmacodynamics and pharmacokinetics (i.e., how a drug affects an organism and how an organism affects a drug, respectively) are determined. Drug safety is evaluated in phase 1, efficacy is assessed in phase 2, and both are confirmed in phase 3 at a large scale. Phase 4 studies or post-marketing surveillance studies are conducted after a drug has been approved. The sponsoring firm, typically a pharmaceutical company, along with collaborators involved in conducting trials, needs to engage multiple tests sites (often in various locations) and recruit, treat, and test hundreds or even thousands of volunteers. A large portion of R&D expenditure goes towards clinical trials. DiMasi *et al.* (2016) estimate the mean expenses for phases 1, 2, and 3 to be $25.3 million, $58.6 million, and $255.4 million, respectively. R&D costs have rapidly escalated in the past decades (Rafols *et al.* 2014). This has been the result of larger and more complex trials, a greater focus on chronic diseases and high failure rates for drugs (less than 12% of candidate medicines going into phase 1 are subsequently approved) (PhRMA 2016). To shorten development times and contain costs, pharmaceutical firms have undertaken a variety of

measures such as mergers and acquisitions, downsizing in-house development efforts and instead outsourcing R&D activities (Rafols *et al.* 2014). The outsourcing of clinical trials to contract research organizations (CROs) has caused CROs to flourish into a multibillion-dollar industry (Betcheva and Erhun 2018). Other entities involved with the conduct of trials include academic institutions, hospitals, biotechnology companies, research institutes, government agencies, and nonprofits, among others. The pharmaceutical R&D SC is better depicted by an ecosystem of various entities which provide different resources and capabilities (see Figure 4 adapted from PhRMA (2016)). For instance, academic institutions and biotechnology firms provide basic research, expertise, and technologies, while pharmaceutical firms offer funding and capacity for full-scale clinical development. Relationships between entities range from purely transactional to more integrated partnerships involving risk and revenue sharing (such as joint ventures among large pharmaceutical companies).

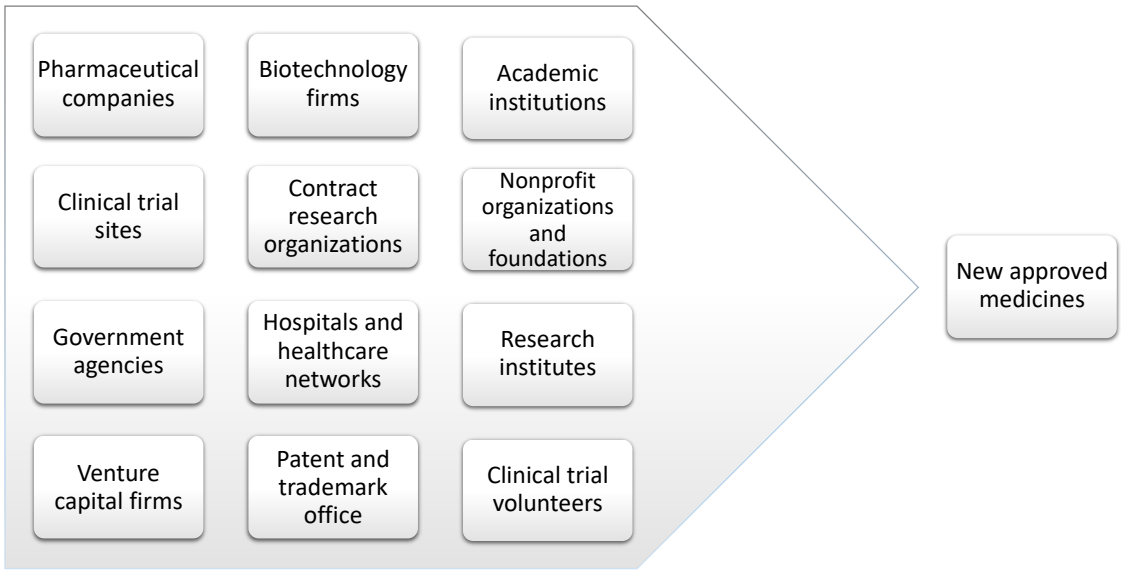

Figure 4: Pharmaceutical innovation and R&D SC (Adapted from PhRMA (2016)).

Partnerships between small biotechnology firms and pharmaceutical companies are vital for healthcare innovation. Savva and Scholtes (2014) analyze and compare three contractual arrangements in this setting: pure co-development, licensing, and co-development with opt-out options. Employing a model that incorporates both technological and commercial uncertainty of projects, the authors show that introducing an option clause in co-development arrangements alleviates inefficient abandonments of profitable projects and reduces the risk that the biotechnology will run out of capital. Bhattacharya *et al.* (2015) study pharmaceutical R&D contractual arrangements with biotechnology firms burdened by various agency issues. The authors formulate a sequential game between a risk-averse provider and a risk-neutral client. They compare two contract types (milestone-based options contracts and buyout option contracts) and show that from the perspective of the pharmaceutical company, milestone-based option contracts, consisting of milestone payment and a fixed fee, always attain the first-best outcome given that the biotechnology firm has some bargaining power.

Motivated by the lack of operational decision support research in the context of clinical trials, Kouvelis *et al.* (2017) seek to provide insights as to how sponsoring firms or administering CROs can determine when and how many test sites should be opened and the number of patients to enroll over time. The problem is modeled under a dynamic program that has the objective of maximizing the net present value of a drug. Trial costs, drug quality, interim analyses of clinical results, the likelihood of approval as well as the expected commercial value after approval are considered in the formulation. The authors characterize the optimal policy as a series of thresholds on both decision variables.

Advancements in technology and AI provide opportunities for personalization, efficiency, and alignment in pharmaceutical SCs. For example, Healx (a Cambridge-based tech venture) focuses on drug development for rare diseases in the emerging field of personalized medicine (Kavadias *et al.* 2016). Rare diseases are often ignored by pharmaceutical companies due to their small market potential and expensive drug development process. To remedy this, guided by a pharmacology team, Healx uses its proprietary AI-based tool (Healnet) to identify and repurpose existing drugs to treat rare diseases. Healx partners closely with patient groups to understand the clinical need and disease information. Quality curated data is then fed into Healnet to predict treatments, which are subsequently reviewed by expert pharmacologists. This results in a faster and cheaper approach to developing treatments for rare diseases (Healx 2019).

3.2. Manufacturing & distribution SCs. Narayana *et al.* (2014) present a systematic review of research on pharmaceutical SCM. The authors identify four key customer healthcare needs for pharmaceuticals: (1) availability, (2) access, (3) affordability, and (4) safety, and discuss how research has analyzed the final value delivered to customers through the SC. They go onto suggest that research has traditionally focused on efficiency improvements and that there is an emerging interest in process analysis and technology implementation. Figure 5 is an adapted depiction of a representative pharmaceutical manufacturing and distribution SC from Narayana *et al.* (2014).

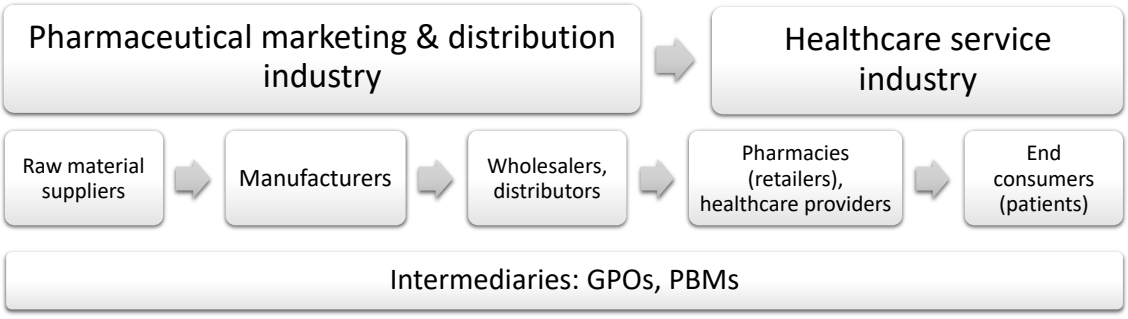

Figure 5: A representative pharmaceutical manufacturing and distribution SC (Adapted from Narayana *et al.* (2014)).

Privett and Gonsalvez (2014) prioritize the top 10 global pharmaceutical SC challenges. Shortage avoidance is amongst the ranked. Drug shortages are both costly (since alternative therapies must be sought) and lead to social welfare loss in terms of suboptimal patient outcomes. Jia and Zhao (2017) study how to minimize shortages for generic sterile injectable drugs, which possess particular characteristics rendering them vulnerable to shortfalls. These drugs have small profit margins making them unattractive to manufacturers. Producers thus allocate low capacity towards such drugs. Worse still, due to demanding storage environments, holding these drugs is costly. The authors model the hSC composed of a manufacturer, a group purchasing organization (GPO), the government, and a healthcare provider and show that a price increase combined with a strong failure-to-supply clause leads to a Pareto-improvement that is effective in addressing shortages.

Another prevalent area of research is the role of intermediaries. Pharmacy benefit manufacturers (PBMs) play an intermediary role between pharmaceutical manufacturers and downstream drug clients such as employers, insurers, and government payers. PBMs create value through the administration of drug claims, negotiation of wholesale prices and design of tiered formularies. Kouvelis *et al.* (2015) evaluate the pricing and formulary decisions of PBMs. GPOs are largely involved in healthcare product procurement and play an intermediary role between hospitals and manufacturers. A 2008 study shows that in the US, 80% of hospitals routed 50% of their pharmaceutical spending through GPOs (Burns and Lee 2008). GPOs offer potential cost reductions for hospitals, as contracting for a group of hospitals' combined purchase quantity allows a GPO to spread its fixed contracting cost over many members. For manufacturers, selling through a GPO offers the opportunity to sell higher volumes. In return, manufacturers pay the GPO a percentage of their revenue contracted through the GPO, termed the contract administration fee (CAF), whereas hospitals may need to pay a membership fee. Hu *et al.* (2012) and Saha *et al.* (2019) examine the impact of GPOs on hSCs and address the controversy around CAFs.

There has been a shift toward value-based healthcare in the pharmaceutical industry. In particular, payers have increasingly employed outcome-based contracting with pharmaceutical companies. This purchasing strategy ties reimbursement to patient outcomes (i.e., companies are paid more when medicines work well). It is important to note that, this type of reimbursement scheme relies on having the appropriate supporting technology and processes in place (i.e., the ability to accurately measure/ monitor patient outcomes). Industry analysts and researchers have brought up various benefits and drawbacks of this reimbursement scheme. However, more work is needed to thoroughly evaluate the ramifications of this payment scheme for different stakeholders such as manufacturers, payers, and patients.

4. Blood SCs

Donated blood and blood products are used in the treatment of various conditions (such as anemia) and in blood transfusions for patients undergoing surgery or those who have suffered an injury. Figure 6 presents a representative blood SC resembling a diagram in Fontaine *et al.* (2009). In their paper, the authors discuss several distinguishing features of blood SCs. Blood cannot be manufactured and can only originate from donors, which constrains supply. There is a lead-time

to blood utilization, as donated blood has to undergo screening tests and needs to be processed before it can be transfused. Furthermore, the short shelf life of blood products (cryoprecipitate (cryo), plasma, red cells, whole blood, and platelets has a shelf life of 1 year, 1 year, up to 42 days, 21-35 days, and 5 days, respectively (The American National Red Cross 2019)) contributes to significant wastes resulting from outdated units. Lastly, mismatches between supply and demand frequently occur leading to excess inventory (unused blood) or shortages. Several researchers have explored improvement opportunities in the collection, as well as the inventory management and allocation, of blood. Chung and Erhun (2013) consider supply contracts for blood with two periods of shelf life ("young" and "old" units). The authors demonstrate the channel-coordinating conditions for three commonly employed industry contracts. For a thorough analysis of blood SCs, readers are referred to Pierskalla (2005).

Figure 6: A representative blood SC.

Ayer *et al.* (2019) state that because of the importance, limited supply, and perishability of blood products, effective management of blood collection is critical for high-quality healthcare delivery. The authors examine the cryo collection. They formulate a mathematical model to identify when and from which sites cryo should be collected such that weekly collection costs are minimized while at the same time ensuring that a weekly target is met. The authors' proposed collection model has since been implemented at the American Red Cross' largest manufacturing facility and the American Red Cross has realized significant benefits as a result of the implementation.

Regional blood banks (RBBs) supply hospitals in their service areas. Due to the scarcity of blood supply, it is common for RBBs to have to ration blood products among the hospitals they serve. Because of this supply uncertainty, hospitals tend to over-order to ensure a larger share of the rationed supply. Paul *et al.* (2019) argue that over-ordering causes an increase in spoilage, which ultimately imposes a cost on the SC as well as a social welfare loss. The authors consider various contractual arrangements in an attempt to arrive at a contract that incentivizes hospitals not to inflate orders, while at the same time ensures the equitable allocation of blood. They demonstrate that a shortage-subsidy contract, which offers a per-unit subsidy for every unit of shortage experienced by a hospital, induces uninflated ordering by hospitals.

The management of blood, from collection to transfusion, is a critically important and often challenging undertaking. However, there is an extensive body of literature on the SCM of perishable products. Therefore, we underscore the potential to apply learnings and strategies from other sectors, such as the food industry, in the management of blood SCs and vice versa.

5. Organ transplantation SCs

Each year, hundreds of thousands of patients around the world wait for organs but only a fraction are lucky enough to undergo transplantation, and many die each day waiting for a transplant, due to a large gap between supply and demand. Organs can be removed for transplantation from living or deceased donors. Countries follow various policies with which legal consent is gained for obtaining organs. For instance, Australia, Canada, the US, and the UK have an opt-in policy requiring explicit consent. On the other hand, in countries like France, Italy, and Sweden, an opt-out policy or "presumed consent" is employed. The impact these policies have on donation rates has been a subject of great interest for researchers and policy-makers. Exacerbating the shortage issue, not all organs donated are viable for use. Furthermore, in some cases, perfectly viable organs are wasted due to inefficiencies in the organ transplantation process caused by the level of coordination required across parties involved such as ED units and ICU staff (Barrow 2012). In addition, donated organs need to be matched to patients based on many factors such as blood type, body size, and patient availability. Concerning living donor donations, Glorie *et al.* (2014) describe kidney exchanges in cycles, which allow multiple donors to donate their kidneys, and multiple patients to receive kidneys that are compatible with their medical conditions. Unlike blood donations, organ donations require simultaneity to prevent organ donors from reneging after their intended recipient has received a transplant from another donor. Because of this simultaneity, the length of cycles is limited to the number of logistically feasible simultaneous transplants. Figure 7 depicts a closed organ SC, in which each station has an incompatible pair comprised of a donor and a recipient. To form compatible matches, each patient receives an organ from the paired donor of another patient in a cyclic manner. Other organ SCs may have very different structures from the one shown in Figure 7, depending on the allocation mechanisms in place. For example, Su and Zenios (2006) discuss a kidney SC that is characterized by n transplant queues corresponding to n candidate types. Aside from simultaneity, another issue concerning organ SCs is that there are significant disparities in the wait time and access to organs across different geographical areas. To alleviate geographic inequality in the US context, Ata *et al.* (2017) propose the utilization of affordable jet services to enable patients to list in multiple, and possibly distant, donation service areas.

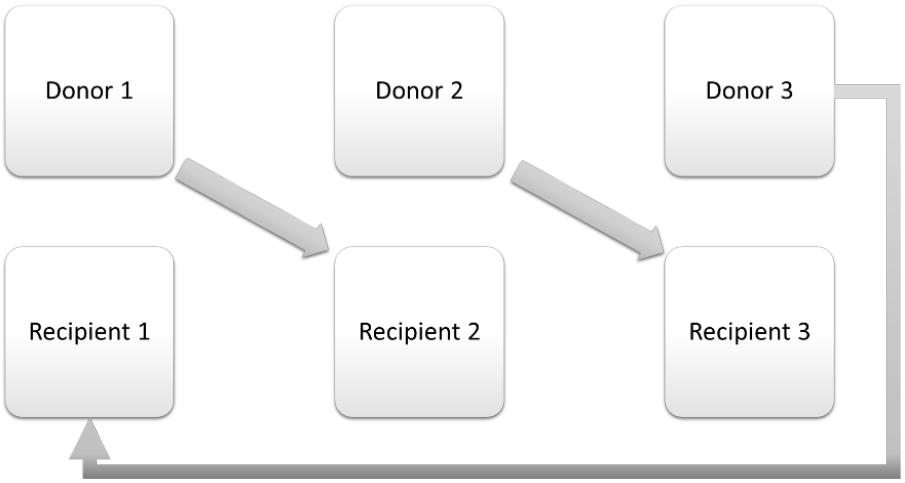

Figure 7: A closed organ SC.

Altruistic or non-directed donations from living donors have also gained ground. NHS Blood and Transplant reports that ever since a change in the law a decade ago (permitting donors to give their organs to people they have never met), more than 500 people have helped save the life of a stranger (NHS Blood and Transplant 2016). Altruistic donations can potentially multiply the number of recipients benefitting from each donation as they can link several pairs of incompatible donor and recipient pairs to form a donation chain (Montgomery *et al.* 2006). This domino effect works through the initiation of a chain of matches (an altruistic donation is matched to a recipient who has a willing but incompatible donor. Consequently, the incompatible donor can give their organ to the next compatible recipient, and so on (Montgomery *et al.* 2006)). Researchers have evaluated organ exchange cycles and chains and have addressed the question of whether transplants should be performed simultaneously or non-simultaneously. The severe shortage in available organs for transplantation is a clear catalyst for future research that aims to improve the obtainment, the matching of donors and recipients, and the allocation of organs.

6. Vaccine SCs

Influenza spreads rapidly around the world in seasonal epidemics and carries considerable financial and human implications (such as lost productivity). Vaccination protects against infection. In addition, it provides a positive externality, as vaccinated individuals decrease the infection risk of their close contacts, thus reducing the impact of outbreaks (Arifoglu *et al.* 2012). Figure 8 presents a simplified vaccine SC. Vaccine SCs resemble traditional commercial SCs, with a key difference being that healthcare providers (such as hospitals and clinics) assume the role of retailers. Vaccine SCs exhibit two specificities: uncertain demand due to the unpredictability of flu prevalence and uncertain production yield arising from the biological composition of the vaccine. Further complicating matters, vaccine manufacturers do not decide on the composition of their vaccines. Instead, an external committee determines this. For

example, in the US, the VRBPAC makes recommendations to the FDA about the annual vaccine composition in February or March of each year for the upcoming flu season that begins the following October (Dai *et al.* 2016). Long lead-times arise due to this complexity of vaccine production.

Figure 8: A simplified vaccine SC.

Dai *et al.* (2016) analyze contracting in the influenza vaccine SC. If manufacturers wait for a vaccine composition decision (by an external committee) prior to initiating production, vaccines may not be delivered on time due to long and uncertain lead times. The result is diminished end consumer demand. This, in turn, motivates retailers to order a low quantity, which further disincentives manufacturers to improve on-time delivery. If, on the other hand, manufacturers engage in early production, on-time delivery is improved but manufacturers bear the risk of having vaccines discarded should the composition differ from the final decision of the committee. It is shown that wholesale contracts, as well as other commonly used contracts in the industry (delivery-time-dependent quantity flexibility contract and late rebate contract) which employ a penalty clause for late delivery, fail to coordinate the SC. The researchers show that a properly designed buyback and late rebate contract can not only coordinate the SC but also allow for flexibility in the division of profits.

From a committee's perspective, Cho (2010) presents research to aid the decision between retaining the current virus strain, changing to a new strain, or deferring the decision. The choice to retain the current strain leads to lower production yield uncertainty, but at the same time runs the risk of being less effective should a new virus strain spread. Conversely, the choice to defer the decision offers the benefit of acquiring more information, and thus, reducing the risk that the wrong strain will be pursued. However, delaying the decision can result in a supply shortage (due to the above-discussed reasons presented in Dai *et al.* (2016)). Cho (2010) offers an optimal threshold policy concerning the committee's decision.

The idiosyncrasies of the vaccine SC have attracted substantial attention from OM and SCM researchers. In recent years, there has been a rising interest in employing various data such as social media and online activity to forecast flu outbreaks. Predicting influenza activity can shed light on when healthcare practitioners can expect to see a rise in demand for their services. This, in turn, can assist providers in making operational decisions such as staffing. An example of this is Google Flu Trends (GFT), which monitored and analyzed Google search queries to estimate flu prevalence. The project began in 2008 but was abandoned within a few years following issues related to the accuracy of predictions (the flu prevalence predicted by GFT from 2011-2013 was wrong in 100 out of 108 weeks (McDonagh 2018)). With the growing popularity of big data, the GFT case shows that caution is warranted. Researchers have pointed to "big data hubris"–the "assumption that big data are a substitute for, rather a supplement to, traditional data collection

and analysis"–to the downfall of GFT (Lazer *et al.* 2014). Lazer *et al.* (2014) promote a focus on an "all data revolution" rather than a "big data revolution," one in which data from traditional and new sources are used to provide a deeper and more comprehensive understanding of the world (Lazer *et al.* 2014). Future research should, therefore, aim to incorporate and combine various analytic tools and approaches to guide decision making.

7. Health humanitarian SCs

Over the last decade, the human and economic impact of disasters has been substantial; natural and man-made disasters have affected 1.7 billion people worldwide, caused $1.4 trillion in damage and have taken the lives of 0.7 million people (UNISDR 2016). In the past few decades, the frequency of disasters, and resulting damage, have dramatically increased. Social and environmental trends may shed light on the increasing impact of catastrophes. Urbanization arising from economic development has made larger populations more vulnerable to disasters Exacerbating the problem, climate change has contributed to the severity of natural disasters. In addition, man-made disasters due to political instability, terrorism, and war have also grown. To deal with the consequences of disasters, a variety of actors ranging from government, donors, nongovernmental organizations (NGOs), non-profit organizations, media, military, and corporations partake in relief efforts (Ertem *et al.* 2010).

Efficient and effective SCs thus play an imperative role in saving lives and assisting those affected. A representative humanitarian SC and its various stakeholders are shown in Figure 9. Humanitarian SCs are often unstable because of polarized donations and the competitive nature of fund-raising from private donors (Oloruntoba and Gray 2006). Compared to commercial SCs, the successful execution of operations and coordination is more difficult to achieve in humanitarian SCs. Wagner and Thakur-Weigold (2018) analyze and categorize the root causes of dysfunctional operations in humanitarian SCs into three causal types: environment and system, organization and leadership, and staffing and the individual. Concerning environment and system, time pressure, budget constraints, inadequate infrastructure and, delayed information due to geographic disparities, are identified as causal factors. The lack of emphasis on the strategic importance of logistics and SCM, siloed behavior resulting from functional specialization, local performance metrics disregarding end-to-end SC requirements, and excessive pre-positioning of safety stock, all relate to organization and leadership. Lastly, turnover which hinders know-how (and know-who) accumulation, incentives favoring "doing" over "reporting" or "planning," a lack of trust, in addition to, the diversity of staff education and experience, are sources of dysfunctionality relating to staffing and the individual. The fact that these SCs function in complex and dangerous environments with a lot of uncertainty, risk, and ambiguity also complicates operations. Furthermore, fewer technology and logistics software is available to track and maintain data (Ertem and Buyurgan 2013). Unlike profit-maximizing SCs, humanitarian SCs are not necessarily regulated through price and the main objective of actors involved is to minimize mortality and alleviate suffering (Ertem and Buyurgan 2013). Humanitarian SCs are characterized by zero lead times as providing relief immediately after the onset of a disaster is of utmost importance (Ertem *et al.* 2010).

Figure 9: A representative humanitarian SC (Adapted from Wagner and Thakur-Weigold (2018)).

Health organizations and agencies have long been concerned with the issue of malaria control. Although malaria is a treatable disease, stock-outs of medications commonly occur in developing countries, partly as a result of problems in the SC. Parvin *et al.* (2018) analyze the distribution of artemesinin combination therapies (ACTs), a form of malaria treatment, in Malawi's three-tiered centralized health system. In this setup, central warehouses and regional hospitals in the first tier deliver to district hospitals in the second tier, who subsequently supply community hospitals in the third tier. The authors outline a two-stage transportation plan that optimizes ACT delivery both at a strategic and tactical level. The first stage determines the initial round of shipments sent prior to the commencement of malaria season, from each central warehouse to each district hospital, and from each distinct hospital to each local clinic. In the second stage, the authors consider two recourse actions (*transshipment* across facilities and *delayed shipment* in which some ACT is held back at district hospitals) to address shortage once malaria season begins and demand is realized.

Ensuring coordination between the wide array of entities which make up humanitarian SCs is greatly important towards the execution and efficiency of humanitarian operations. Entities often have different objectives, capabilities, and constraints. Especially in the face of sudden-onset disasters, actors providing aid may need to assemble and familiarize themselves with the context, situation (e.g., what has happened, what may follow, etc.) and other entities involved in relief efforts in short periods of time. Balcik *et al.* (2010) discuss and present an overview of coordination in relief SCs. The authors explain the challenges in achieving coordination and discuss the current coordination mechanisms utilized in commercial SCs and their adaptability to relief SCs. We encourage further research directed towards enhancing coordination and integration in health humanitarian SCs in an attempt to provide aid recipients with more, higher quality, and faster access to healthcare.

8. Concluding Remarks

The global population is on the rise and aging. There is an increasing burden of disease brought about by the prevalence of chronic conditions. Many individuals are living with multiple co-morbidities and have complex needs. As a result, the healthcare sector faces serious clinical, operational, and financial challenges. To manage the population's health needs, great efforts are required for health maintenance, as well as the prevention, diagnosis, and treatment of diseases. Well-functioning SCs underpin effective and efficient healthcare delivery. Therefore, how SCs are designed, operated and managed carries importance for individuals' health status, life

expectancy, and quality of life. For each above-discussed hSC, we have proposed avenues for future research. In the current landscape, we feel three key research areas have the potential to establish the provision of timely, high quality, accessible, and equitable healthcare at a lower cost (Betcheva *et al.* 2019): new models of care, new reimbursement schemes, and emerging health technologies and innovations. We refer the reader to Keskinocak and Savva (2019) and KC *et al.* (2019) who discuss these research opportunities, among others, in their contemplation of the future of healthcare operations.

We foresee significant developments in hSCs in the future. In particular, we anticipate changes in the resources (including the workforce), the processes and strategies, as well as the infrastructure of hSCs. It is reasonable to expect that more sophisticated medical technologies and devices will continually emerge with the rapid advancement of technology. This necessitates a workforce with technical capabilities, and clinician training should reflect this. New technologies and innovations also offer significant opportunities for healthcare provision in the developing world. As an example, take organizations like Zipline which are delivering medical products (such as blood and medication) through the use of drones. Furthermore, robotics and digital technologies are increasingly entering healthcare systems. This offers the potential to address staff shortfalls. For instance, physicians spend a portion of their time with mundane tasks such as computer entries. Through automation and the downshifting of tasks to lower-tier personnel, physicians' time is protected for activities that add more value towards patient care. Technologies, such as AI, are also supporting clinical decision making.

With a focus on the patient as a whole, we expect care delivery to aim attention at health maintenance rather than the treatment of disease. Such a shift will require more meaningful patient involvement and a sense of responsibility for their own health. This needs to be facilitated by healthcare providers who should promote self-care by ensuring information and support is available and accessible. We also note that technology, such as wearable devices, can enable self-monitoring. Devices and developments in telemedicine can also change the infrastructure of hSCs. As care moves closer to patients' home, we envision internet of things (IoT) to take on a greater presence in healthcare delivery whilst a lower amount of a patient's care to be delivered in hospital settings.

Furthermore, technology is altering how hSC members communicate and collaborate. Electronic data sharing allows providers to make collective decisions on shared information. To gain more value out of increased connectivity, communication platforms should be integrated, and data should be standardized, across providers. This ensures that professionals access the same data and "speak the same language." Moreover, data quality should be bolstered by improving the richness and accuracy of entries. The wealth of patient data will also facilitate developments in personalized medicine and data-driven (clinical and operational) decision making. We note more research is required on how to best utilize the accumulation of data. In addition, dealing with issues regarding confidentiality and data protection becomes key in ensuring patients' and providers' trust.

Overall, in managing the population's increasing healthcare needs, future hSCs need to promote a focus on health maintenance, pursue a holistic and collaborative approach to healthcare, and to foster a tech-forward and innovative mindset.

Bibliography

1. Adida, E., F. Bravo. 2019. Contracts for healthcare referral services: Coordination via outcome-based penalty contracts. *Management Science* **65**(3) 1322-1341.
2. Arifoglu, K., S. Deo, S.M.R. Iravani. 2012. Consumption externality and yield uncertainty in the Influenza vaccine supply chain: Interventions in demand and supply sides. *Management Science* **58**(6) 1072-1091.
3. Ata, B., A. Skaro, S. Tayur. 2017. Organjet: Overcoming geographical disparities in access to deceased donor kidneys in the United States. *Management Science* **63**(9) 2776-2794.
4. Ayer, T., C. Zhang, C. Zeng, C.C. White III, V.R. Joseph. 2019. Analysis and improvement of blood collection operations. *Manufacturing & Service Operations Management* **21**(1) 29-46.
5. Balcik, B., B.M. Beamon, C.C. Krejci, K.M. Muramatsu, M. Ramirez. 2010. Coordination in humanitarian relief chains: Practices, challenges and opportunities. *International Journal of Production Economics* **126** 22-34.
6. Barrow, M. 2012. Patients die waiting for organs that go to waste. *The Times (London),* January 30.
7. Beech, J., S. Bottery, A. Charlesworth, H. Evans, B. Gershlick, N. Hemmings, C. Imison, P. Kahtan, H. McKenna, R. Murray, Palmer B. 2019. *Closing the Gap - Key Areas for Action on the Health and Care Workforce.* The Health Foundation, The King's Fund, Nuffield Trust. Report. https://www.kingsfund.org.uk/publications/closing-gap-health-care-workforce. Accessed June 30, 2019.
8. Betcheva, L., F. Erhun. 2018. Which stage of the industry lifecycle do clinical research organizations (CROs) currently reside in? An exploratory analysis using clinical trials data. *MRes Dissertation*. Judge Business School, University of Cambridge, UK. Available upon request from the authors.
9. Betcheva, L., F. Erhun, H. Jiang. 2019. A supply chain view of healthcare: Learnings and a consideration of the future. *Working paper.* Judge Business School, University of Cambridge, UK. Available upon request from the authors.
10. Bhattacharya, S., V. Gaba, S. Hasija. 2015. A comparison of milestone-based and buyout options contracts for coordinating R&D partnership. *Management Science* **61**(5) 963-978.
11. Blouin, R.A., M.L. Adams. 2017. The role of the pharmacist in health care: Expanding and evolving. *North Carolina Medical Journal* **78**(3) 165-167.
12. Blumberg, D.F. 2004. *New Strategic Directions in Acquiring and Outsourcing High-tech Services by Hospitals and Implications for Clinical Engineering Organizations and ISOs.* Clinical Engineering Handbook Academic Press Series in Biomedical Engineering.
13. Bottery, S., M. Varrow, R. Thorlby, D. Wellings. 2018. A fork in the road: Next steps for social care funding reform. https://www.kingsfund.org.uk/sites/default/files/2018-05/A-fork-in-the-road-next-steps-for-social-care-funding-reform-May-2018.pdf. Accessed June 30, 2019.
14. Bretthauer, K.M., S.H. Heese, H. Pun, E. Coe. 2011. Blocking in healthcare operations: A new heuristic and an application. *Production and Operations Management* **20**(3) 375-391.

15. Brindle, D. 2017. Buurtzorg: The Dutch model of neighbourhood care that is going global.https://www.theguardian.com/social-care-network/2017/may/09/buurtzorg-dutch-model-neighbourhood-care Accessed July 11, 2019.
16. Buchan, J., A. Charlesworth, B. Gershlick, I. Seccombe. 2019. *A Critical Moment: NHS Staffing Trends, Retention and Attrition.* The Health Foundation. https://www.health.org.uk/sites/default/files/upload/publications/2019/A%20Critical%20Moment_1.pdf. Accessed June 30, 2019.
17. Burns, L.R., J.A. Lee. 2008. Hospital purchasing alliances: Utilization, services, and performance. *Health Care Management Review* **33**(3) 203-215.
18. Calsyn, M., E.O., Lee. 2012. Alternatives to fee-for-service payments in health care. *Center for American Progress.* https://www.americanprogress.org/wp-content/uploads/2012/09/FeeforService-1.pdf. Accessed July 17, 2019.
19. Chan, T.H., F. de Véricourt, O. Besbes. 2019. Contracting in medical equipment maintenance services: An empirical investigation. *Management Science* **65**(3) 1136-1150.
20. Charles, A. 2019. Community health services explained. *The King's Fund.* https://www.kingsfund.org.uk/publications/community-health-services-explained#how-are-they-organised. Accessed July 16, 2019.
21. Charlesworth, A., P. Johnson. 2018. *Securing The Future: Funding Health and Social Care to The 2030s.* Institute for Fiscal Studies, Health Foundation.
22. Cho, S-H. 2010. The optimal composition of influenza vaccines subject to random production yields. *Manufacturing & Service Operations Management* **12**(2) 256-277.
23. Christopher, M.L. 2016. *Logistics and Supply Chain Management.* 5th ed. Pearson Education, Harlow, England.
24. Chung, Y.T. and F. Erhun. 2013. Designing supply contracts for perishable goods with two periods of shelf life. *IIE Transactions* **45**(1) 53-67.
25. Cruz, A.M., A.M.R. Rincon. 2012. Medical device maintenance outsourcing: Have operation management research and management theories forgotten the medical engineering community? A mapping review. *European Journal of Operational Research* **221**(1) 186-197.
26. Dai, T., S-H. Cho, F. Zhang. 2016. Contracting for on-time delivery in the U.S. influenza vaccine supply chain. *Manufacturing & Service Operations Management* **18**(3) 332-346.
27. de Vries, J., R. Huijsman. 2011. Supply chain management in health services: An overview. *Supply Chain Management: An International Journal* **16**(3) 159-165.
28. DiMasi, J.A., H.G. Grabowski, R.W. Hansen. 2016. Innovation in the pharmaceutical industry: New estimates of R&D costs. *Journal of Health Economics* **47** 20-33.
29. Ertem, M.A., N. Buyurgan. 2013. A procurement auctions-based framework for coordinating platforms in humanitarian logistics. V. Zeimpekis, S. Ichoua, I. Minis eds., *Humanitarian and Relief Logistics.* Springer, New York, NY.
30. Ertem, M.A., N. Buyurgan, M.D. Rossetti. 2010. Multiple-buyer procurement auctions framework for humanitarian supply chain management. *International Journal of Physical Distribution & Logistics Management* **40**(3) 202-227.
31. Fontaine, M.J., Y.T. Chung, W.M. Rogers, H.D. Sussmann, P. Quach, S.A. Galel, L.T. Goodnough, F. Erhun. 2009. Improving platelet supply chains through collaborations between blood centers and transfusion services. *Transfusion* **49**(10) 2040-2047.

32. Freeman, M., S. Robinson, S. Scholtes. 2018. Gatekeeping under congestion: An empirical study of referral errors in the emergency department. Working paper. Judge Business School, University of Cambridge, UK.
33. Gershlick, B., Z, Firth. 2017. Provision of community care: Who, what, how much? *The Health Foundation Briefing.* https://www.health.org.uk/publications/provision-of-community-care-who-what-how-much Accessed July 16, 2019.
34. Glorie, K.M., J.J. van de Klundert, A.P.M. Wagelmans. 2014. Kidney exchange with long chains: An efficient pricing algorithm for clearing barter exchanges with branch-and-price. *Manufacturing & Service Operations Management* **16**(4) 498-512.
35. He, W., D.E., Goodkind, P. Kowal. 2016. *An Aging World: 2015. International Population Reports* (P95/09-1). Washington, DC: U.S. Government Printing Office.
36. Healx. 2019. Accelerating treatments for rare diseases https://healx.io/. Accessed July 5, 2019.
37. Hu, Q., L.B. Schwarz, N.A. Uhan. 2012. The impact of group purchasing organizations on healthcare-product supply chains. *Manufacturing & Service Operations Management* **14**(1) 7-23.
38. Jia, J., H. Zhao. 2017. Mitigating the U.S. drug shortages through Pareto-improving contracts. *Production and Operations Management* **26**(8) 1463-1480.
39. Jain, N., S. Hasija, D.G. Popescu. 2013. Optimal contracts for outsourcing of repair and restoration services. *Operations Research* **61**(6) 1295-1311.
40. Jiang, H., Z. Pang, S. Savin. 2012. Performance-based contracts for outpatient medical services. *Manufacturing & Service Operations Management* **14**(4) 654-669.
41. Joynt, K.E., J. Figueroa, J. Oray, and A.K. Jha. 2016. Opinions on the hospital readmission reduction program: Results of a national survey of hospital leaders. *American Journal of Managed Care* **22**(8) e287–e294.
42. Karmarkar, U.S., G. Roels. 2015. An analytical framework for value co-production in services. *Service Science* **7**(3) 163-180.
43. Kavadias, S., K. Ladas, C. Loch. 2016. The transformative business model. *Harvard Business Review.* October issue.
44. KC, D.S., S. Scholtes, C. Terwiesch. 2019. Empirical research in healthcare operations: Past research, present understanding, and future opportunities. Forthcoming in *Manufacturing & Service Operations Management.*
45. Keskinocak, P., N. Savva. 2019. A review of the healthcare-management (modeling) literature published at M&SOM. Forthcoming in *Manufacturing & Service Operations Management.*
46. Kouvelis, P., J. Milner, Z. Tian. 2017. Clinical trials for new drug development: Optimal investment and application. *Manufacturing & Service Operations Management* **19**(3) 437-452.
47. Kouvelis, P., Y. Xiao, N. Yang. 2015. PBM competition in pharmaceutical supply chain: Formulary design and drug pricing. *Manufacturing & Service Operations Management* **17**(4) 511-526.
48. Lazer, D., R. Kennedy, G. King, A. Vespignani. 2014. The parable of Google Flu: Traps in big data analysis. *Science* **343**(6176) 1203-1205.

49. Livi-Bacci, M. 2001. *A Concise History of World Population*. 3rd Edition, Oxford, UK, Blackwell.
50. Lu, S.F., L.X. Lu. 2017. Do mandatory overtime laws improve quality? Staffing decisions and operational flexibility of nursing homes. *Management Science* **63**(11) 3566-3585.
51. Lu, L.X., S.F. Lu. 2018. Distance, quality, or relationship? Interhospital transfer of heart attack patients. *Production and Operations Management* **27**(12) 2251-2269.
52. Lu, S.F., H. Rui, A. Seidmann. 2018. Does technology substitute for nurses? Staffing decisions in nursing homes. *Management Science* **64**(4) 1842-1859.
53. Malkin, R., C. Whittle. 2014. Biomedical equipment technician capacity building using a unique evidence-based curriculum improves healthcare. *Journal of Clinical Engineering* **39**(1) 37-44.
54. McDonagh, L. 2018. Google Flu Trends is dead - long live Google Trends? https://blogs.ucl.ac.uk/pcph-blog/2018/01/23/google-flu-trends-is-dead-long-live-google-trends/ Accessed July 10, 2019.
55. Mentzer, J., W. DeWitt, J.S. Keebler, S. Min, N.W. Nix, C.D. Smith, Z.G. Zacharia. 2001. Defining supply chain management. *Journal of Supply Chain Management* **22**(2) 1-25.
56. Montgomery, R.A., S.E. Gentry, W.H. Marks, D.S. Warren, J. Hiller, J. Houp, A.A. Zachary, J.K. Melancon, W.R. Maley, H. Rabb, C. Simpkins, D.L. Segev. 2006. Domino paired kidney donation: A strategy to make best use of live non-directed donation. *Lancet* **368** 419-421.
57. Narayana, S.A., R.K. Pati, P. Vrat. 2014. Managerial research on the pharmaceutical supply - A critical review and some insights for future directions. *Journal of Purchasing & Supply Management* **20**(1) 18-40.
58. National Collaboration for Integrated Care and Support. 2013. Integrated Care and Support: Our Shared Commitment. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/198748/DEFINITIVE_FINAL_VERSION_Integrated_Care_and_Support_-_Our_Shared_Commitment_2013-05-13.pdf. Accessed June 30, 2019.
59. National Institute for Health Research. 2019. Physician associates an asset to hospital and surgical teams, study finds. https://www.nihr.ac.uk/news/physician-associates-an-asset-to-hospital-medical-and-surgical-teams-study-finds/10233. Accessed July 15, 2019.
60. NHS Blood and Transplant. 2016. 500 people have now donated a kidney to a stranger. https://www.organdonation.nhs.uk/get-involved/news/500-people-have-now-donated-a-kidney-to-a-stranger/ Accessed July 11, 2019.
61. NHS Digital. 2017. Adult social care activity and finance report, England 2016-17. https://digital.nhs.uk/catalogue/PUB30121. Accessed June 30, 2019.
62. NHS England. 2013. Transforming urgent and emergency care services in England. https://www.nhs.uk/NHSEngland/keogh-review/Documents/UECR.Ph1Report.FV.pdf Accessed July 11, 2019.
63. NHS England. 2019. The physician associate will see you now - new role to assist patients in primary care. Case study. https://www.england.nhs.uk/gp/case-studies/the-physician-associate-will-see-you-now-new-role-to-assist-patients-in-primary-care/ Accessed July 15, 2019.

64. NHS Improvement. 2017. Case studies: Focus on improving patient flow. https://improvement.nhs.uk/documents/1428/Patient_Flow_Guidance_Case_studies_13_July.pdf. Accessed July 17, 2019.
65. OECD. 2016. *Health Workforce Policies in OECD Countries: Right Jobs, Right Skills, Right Places.* OECD Health Policy Studies, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264239517-en. Accessed June 30, 2019.
66. OECD. 2017. Health expenditure and financing. https://stats.oecd.org/Index.aspx?DataSetCode=SHA. Accessed June 30, 2019.
67. Oloruntoba, R., R. Gray. 2006. Humanitarian aid: An agile supply chain? *Supply Chain Management: An International Journal* **11**(2) 115-120.
68. Oxtoby, K. 2009. Professional roles are blurring. *The British Medical Journal.* 10.1136/bmj.a3163
69. Parvin, H., S. Beygi, J.E. Helm, P.S. Larson, M.P. Van Oyen. 2018. Distribution of medication considering information, transshipment, and clustering: Malaria in Malawi. *Production and Operations Management* **27**(4) 774-797.
70. Paul, A., T. Rajapakshe, S. Mallik. 2019. Socially optimal contracting between a regional blood bank and hospitals. *Production and Operations Management* **28**(4) 908-932.
71. PhRMA. 2016. 2016 biopharmaceutical research industry profile. http://phrma-docs.phrma.org/sites/default/files/pdf/biopharmaceutical-industry-profile.pdf. Accessed June 30, 2019.
72. Pierskalla, W.P. 2005. Supply chain management of blood banks. M.L. Brandeau, F. Sainfort, W.P. Pierskalla, eds., *Operations Research and Health Care. International Series in Operations Research & Management Science, vol 70*. Springer, Boston, MA.
73. Privett, N., D. Gonsalvez. 2014. The top ten global health supply chain issues: Perspectives from the field. *Operations Research for Health Care* **3** 226-230.
74. Rafols, I., M.M. Hopkins, J. Hoekman, J. Siepel, A. O'Hare, A. Perianes-Rodríguez, P. Nightingale. 2014. Big pharma, little science? A bibliometric perspective on big pharma's R&D decline. *Technological Forecasting & Social Change* **81** 22-38.
75. Riley, J.C. 2005. Estimates of regional and global Life expectancy,1800–2001. *Population and Development Review* **31**(3) 537-543.
76. Robertson, R., S. Gregory, J. Jabbal. 2014. *The social care and health systems of nine countries.* The King's Fund, London. https://www.kingsfund.org.uk/sites/default/files/media/commission-background-paper-social-care-health-system-other-countries.pdf. Accessed June 30, 2019.
77. Royal College of Nursing. 2016. The Buurtzorg Nederland (home care provider) model: Observations for the United Kingdom (UK). *RCN Policy and International Department-Policy Briefing.* https://www.rcn.org.uk/-/media/royal-college-of-nursing/documents/policies-and-briefings/uk-wide/policies/2015/br-0215.pdf Accessed July 11, 2019.
78. Saha, R.L., A. Seidmann, V. Tilson. 2019. The impact of custom contracting and the infomediary role of healthcare GPOs. *Production and Operations Management* **28**(3) 650-667.
79. Savva, N., S. Scholtes. 2014. Opt-out options in new product co-development partnerships. *Production and Operations Management* **23**(8) 1370-1386.

80. Stylianou, N., R. Fackrell, C. Vasilakis. 2017. Are medical outliers associated with worse patient outcomes? A retrospective study within a regional NHS hospital using routine data. *BMJ Open* **7**(5) e015676.
81. Su, X., S.A. Zenios. 2006. Recipient choice can address the efficiency-equity trade-off in kidney transplantation: A mechanism design model. *Management Science* **52**(11) 1647-1660.
82. The American National Red Cross. 2019. Blood components. https://www.redcrossblood.org/donate-blood/how-to-donate/types-of-blood-donations/blood-components.html. Accessed July 10, 2019.
83. The Health Foundation, Nuffield Trust, The King's Fund. 2018. *The Health Care Workforce in England - Make or Break?* https://www.kingsfund.org.uk/publications/health-care-workforce-england. Accessed June 30, 2019.
84. The King's Fund. 2018. Key challenges facing the adult social care sector in England. https://www.kingsfund.org.uk/publications/key-challenges-facing-adult-social-care-sector-England. Brief. Accessed June 30, 2019.
85. The Medical Futurist. 2018. Could A.I. solve the human resource crisis in healthcare? https://medicalfuturist.com/could-a-i-solve-the-human-resources-crisis-in-healthcare Accessed July 9, 2019.
86. Trebble, T.M., N. Hansi, T. Hydes, M.A. Smith, M. Baker. 2010. Process mapping the patient journey: An introduction. *BMJ* 341:c4078
87. UNISDR. 2016. Disaster statistics. https://www.unisdr.org/we/inform/disaster-statistics. Accessed December 20, 2016.
88. Wagner, S.M. and Thakur-Weigold. 2018. Supporting collaboration in humanitarian supply chains - Insights from a design science project. *Production Planning & Control* **29**(14) 1130-1144.
89. Wang, D., D.J. Morrice, K. Muthuraman, J.F. Bard, L.K. Leykum, S.H. Noorily. 2018. Coordinated scheduling for a multi-server network in outpatient pre-operative care. *Production and Operations Management* **27**(3) 458-479.
90. World Health Organization. 2011. *Medical Equipment Maintenance Programme Overview.* Geneva.