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Review

Lean, Six Sigma, and Simulation: Evidence from Healthcare Interventions

Diego Tlapa [1], Ignacio Franco-Alucano [1], Jorge Limon-Romero [1,*], Yolanda Baez-Lopez [1,*] and Guilherme Tortorella [2,3,4]

1 Facultad de Ingeniería, Arquitectura y Diseño, Universidad Autónoma de Baja California, Ensenada 23080, Mexico
2 Department of Mechanical Engineering, University of Melbourne, Melbourne, VIC 3010, Australia
3 IAE Business School, Universidad Austral, Buenos Aires B1630FHB, Argentina
4 Department of Systems and Production Engineering, Universidade Federal de Santa Catarina, Florianopolis 88040, Brazil
* Correspondence: jorge.limon@uabc.edu.mx (J.L.-R.); yolanda@uabc.edu.mx (Y.B.-L.); Tel.: +52-1646-1744-333 (J.L.-R.)

Abstract: In the Industry 4.0 era, healthcare services have experienced more dual interventions that integrate lean and six sigma with simulation modeling. This systematic review, which focuses on evidence-based practice and complies with the PRISMA guidelines, aims to evaluate the effects of these dual interventions on healthcare services and provide insights into which paradigms and tools produce the best results. Our review identified 4018 studies, of which 39 studies met the inclusion criteria and were selected. The predominantly positive results reported in 73 outcomes were mostly related to patient flow: length of stay, waiting time, and turnaround time. In contrast, there is little reported evidence of the impact on patient health and satisfaction, staff wellbeing, resource use, and savings. Discrete event simulation stands out in 74% of the interventions as the main simulation paradigm. Meanwhile, 66% of the interventions utilized lean, followed by lean-six sigma with 28%. Our findings confirm that dual interventions focus mainly on utilization and access to healthcare services, particularly on either patient flow problems or problems concerning the allocation of resources; however, most interventions lack evidence of implementation. Therefore, this study promotes further research and encourages practical applications including the use of Industry 4.0 technologies.

Keywords: lean; six sigma; simulation; industry 4.0; patient flow; wait time; length of stay

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1. Introduction

Since the advent of Industry 4.0, hospitals have accelerated implementing digitalization across all types of processes and settings. This transformation in healthcare, also referred to as Healthcare 4.0 [1–3], has created an environment that also supports the improvement of efficiency and the quality of care. This is evident in how healthcare services have implemented different technologies including simulation [4], automation [5], telemedicine [6], machine learning [7], and big data [8] among others. Particularly, to improve service delivery, healthcare facilities looked toward operation research techniques, simulation, and continuous improvement methods [9]. Among operation research tools, simulation is commonly utilized in healthcare [10] to support decision-making by testing different scenarios, and gaining immediate feedback about proposed changes without compromising patient safety [11].

On the other hand, since the COVID-19 pandemic, the ongoing challenge to increase the quality of care and use resources more efficiently has become more prevalent in the healthcare sector. Among the improvement methodologies, hospitals have implemented several approaches to deal with quality and efficiency, including lean [12], six sigma

(SS) [13], and total quality management [14] among others. Notably, lean interventions are recurrent approaches to reduce non-value-added activities while aiming to increase efficiency. Similarly, six sigma focuses on reducing variation from processes [15–23].

Applications of simulation in healthcare vary in scope, including material flow planning in hospitals [24], COVID-19 RT-PCR testing processes [25], patient scheduling [26], patient registration processing [27], using virtual reality [28], and assessing health technology [29]. On the other hand, lean, SS, and LSS interventions (LSS) have also been implemented with different approaches and goals, e.g., redesigning a supply chain for an operating room [30], improving the discharge process [31], redesigning the scheduling process for elective surgery [32], enhancing the patient flow in emergency department (ED) [33], or improving controlled drug processes [34].

Notably, the dual intervention of improvement approaches (lean, SS, and LSS) and simulation in healthcare has increased in recent years. For instance, lean and system dynamic (SD) simulation for an ICU re-design [35]; just-in-time approach and simulation for inventory management of surgical instruments in operating rooms (OR) [36]; LSS and simulation for reducing the patients' length of stay in the ED [37]; transforming an ED workflow combining lean, machine learning, and simulation [7]; or reducing waiting time through system dynamics and value stream map [27] have not only demonstrated the possibility but also the practicality of dual interventions. Despite the increasing popularity and adoption of LSS and simulation, not all organizations have reported successful outcomes. Particularly, a large number of studies reported only scenarios and metrics after simulation, but did not report on the implementation of the proposed actions which would have served as a means to verify these scenarios [38–40]. In some other cases, studies reported no change or a decline in some metrics after the intervention [41].

The evolution as well as benefits and barriers of LSS in healthcare have been a topic of research in many studies [42–54]. Likewise, numerous reviews examined the use of simulation with different approaches and scopes in healthcare [55–59]. As a dual intervention, LSS and simulation have been reviewed primarily in manufacturing companies [60–62]. However, systematic reviews on dual interventions in healthcare are scarce. We identified only two in existence: one review focused on evidence of simulation and lean [63] while another focused only on obstacles for lean and DES implementation [64]. We did not find reviews focusing on describing the dual interventions of LSS and simulation techniques or on summarizing the results of such interventions. This absence signals that there is still a lack of information on the effects that LSS and simulation have in healthcare services. Therefore, this research focuses on addressing the following research questions.

RQ1. What are the effects of dual interventions of LSS and simulation on healthcare services?
RQ2. How is such a dual intervention of simulation and LSS implemented in healthcare?

Dual intervention entails the use of specific tools. Particularly, different paradigms of simulations have been utilized, including DES [35,36,41,65,66], SD [67–69], and agent-based simulation (ABS) [7]. Although DES is the most common simulation approach, our research also looked at ABS, SD, and other paradigms in order to examine which best fits improvement approaches. Regarding lean and six sigma, different tools have been commonly reported in healthcare, including value stream map (VSM) [70], just-in-time [36], kaizen [9], and design of experiments (DOE) [71]. However, the scarce evidence of such tools within LSS and simulation interventions suggests a need for research to determine what types of paradigms and tools present the best results. In order to provide insights on this, the following research questions were raised:

RQ3. What simulation paradigms have been used to support dual interventions in healthcare?
RQ4. What tools of LSS have been used to support dual interventions in healthcare?

Both improvement methodologies and simulation, are implemented with different purposes in healthcare, thus reporting different measures. Lean has been focused mainly on improving patient flow [12], which is demonstrated by studies reporting improvement in metrics such as the length of stay (LOS) [72,73], the turnaround time (TAT) [74,75], the waiting time [9,76], the turnover time (TOT) [67,77], and the number of patients who left without being seen (LWBS) [7,78]. Similarly, related metrics improved in healthcare by six sigma include the cycle time of patients discharge process [79], TAT [80], appointment lead time [81], and waiting time [82]. Accordingly, simulation studies commonly reported metrics related to time and efficiency, financial and cost savings, allocation of resources and scheduling, quality and defects, or patient health and safety [55]. In this manner, the focus of simulation and LSS, as well as similarities in the type of outcomes to be improved, suggest the benefit of using a joint intervention. However, we did not find studies that review the complementary utilization of LSS and simulation in healthcare. Moreover, the expected improvement in the patient flow, quality of care, and efficiency may result in an improvement in patient and staff satisfaction. Despite the fact that several studies in healthcare reporting LSS [83–85] or simulation [86,87] interventions have also reported measures related to patient or staff satisfaction, we did not identify studies reporting on the effects that the dual intervention has on satisfaction. Based on these arguments, two research questions emerge:

RQ5. What are the complementary roles of simulation and LSS in healthcare?
RQ6. What is the effect on patient and staff satisfaction after a dual intervention?

The organization of this document follows a precise sequence in order to guide this research. A theoretical framework is provided, the methodology followed is described, and the results are presented. Then, a detailed discussion is included aimed to characterize the evolution of the dual interventions. Finally, a conclusion section is provided and future research directions are proposed.

2. Theoretical Framework

2.1. Simulation

Simulation techniques have been used for different purposes [88] and in different areas [89], which can enable the easy examination of the Industry 4.0 phenomenon from different perspectives [90]. Although simulation in healthcare has been utilized since the 1970s, its prevalence nowadays is supported by the advance of technology to capture, communicate, and analyze data in real time. This is more evident, since healthcare systems are largely adaptive human-based systems characterized by uncertainty and variability that require a stochastic approach [91]. In addition, healthcare systems present complexity and dynamism that involve interactions utilizing limited resources (physical and human resources) and less structured processes [92–94]. These features are all strengths of simulation and help to explain why this approach has been so widely used in healthcare applications [91].

2.2. Lean Interventions

Lean originated from the Toyota Production System (TPS), which is used to increase efficiency in manufacturing companies [95], but also TPS has been identified as an effective means to reduce costs and improve outcomes in healthcare [96]. Lean prevails in several healthcare services and specialties, e.g., intensive care units (ICUs) [15], cardiology [16], surgery [17], colonoscopy [97], pathology [18], radiology [98], mental health [99], eye hospitals [19], and clinical laboratories [100]. In doing so, lean reviews a healthcare process to identify the elements of value to the patient, i.e., activities that enhance healthcare quality and promote patient well-being [101]. Similarly, lean identifies waste in processes, i.e., anything other than the minimum amount of equipment, space, or staff time essential to add value to a product or service [102]. Thus, lean classifies activities into two main groups: value-added (VA) activities that contribute directly to patient needs and non-value-added activities (NVA) that waste time, space, or resources [103,104].

2.3. Six Sigma

With roots in manufacturing, six sigma (SS) gained popularity due to its proven success in decreasing defects and reducing costs in companies such as Motorola and General Electric. Due to these results, SS caught the attention of the service sector, including healthcare professionals [105]. The premise of SS is the definition of a measurable quantitative objective [94], also called the "big Y". By focusing on a specific outcome, SS encourages experimentation and analysis of the correspondent independent "X" variables [82,106]. Through this process, SS provides a roadmap that consists of five phases designed to uncover the root cause of a problem: Define, Measure, Analyze, Improve, and Control (DMAIC) [107]. In short, a problem is defined, outcome data are measured and collected, and statistical methods are used to analyze sources of variation. Processes are then adjusted to improve the targeted outcome, and data are collected and analyzed multiple times to check for improvement in error rates. Finally, processes are put in place to ensure continued monitoring of the outcome [13]. Based on statistical analysis, SS emphasizes using data and quantitative methods to drive decisions through a rigorous process to obtain the true source of the problem from the customer's perspective [13,108].

2.4. Main Outcomes in Simulation and Improvement Approaches Interventions

The measurement of the effects of interventions in healthcare such as lean, six sigma, and simulation include several different outcomes similar to those suggested by the Effective Practice and Organization of Care (EPOC) group that categorizes outcomes into main and secondary outcomes [109]. For the main outcomes, previous studies included the 30 day mortality rate [15,110–112]; the readmission or revisit rate [15,110]; LOS [113,114]; TAT [74,75]; TOT [77]; discharge order time [115,116]; patient waiting time [101,117]; boarding time [115,118]; LWBS [7]; and on-time starts [119–121]. It is also noteworthy that different outcomes including the waiting time, LOS, TOT, TAT, and the boarding time might impact patient flow, i.e., the movement of patients through care settings [122]. On the other hand, secondary outcomes focus on metrics such as patient, staff, and stakeholder satisfaction [109].

3. Materials and Methods

Our systematic review adhered to the PRISMA guidelines [123–125] and the Cochrane Handbook [126]. The flowchart (see Figure 1) depicts the phases of the systematic review, while Table S1 (Supplementary Materials) shows all the requirements of the PRISMA checklist. The following subsections describe the methodology used.

3.1. Search Strategy

Our search for studies, which comprised interventions of lean, six sigma as well as simulation published in English from January 2000 until the end of July 2022, included five databases: PubMed-Medline, Cochrane Library, Ebsco-Host, Web of Science, and Scopus; additionally, Google Scholar allowed us to search grey literature. To identify relevant supplemental studies, we also reviewed the references from the acquired search results.

Our search strategy (Table S2 of the Supplementary Materials) followed the guidelines proposed by the EPOC group [109] and the Peer Review of Electronic Search Strategies (PRESS) [127]. The search strategy included the terms associated with the PICOS elements (population, intervention, comparator, outcome, and study design).

3.2. Selection of Studies

We searched for randomized controlled trials (RCTs) and controlled before-after (CBA) studies. Case-control, pre-post, and cohort studies were also included to generalize the effect of the interventions. We included studies reporting the intervention in one or more departments within hospitals for outpatient care, inpatient care, and primary to quaternary care in both the private and public sector. The intervention consists of improvement approaches such as lean (also known as lean thinking, or Toyota production system), six sigma, or lean six sigma in combination with simulation (discrete event simulation, system dynamic simulation, agent-based simulation, and Monte Carlo simulation).

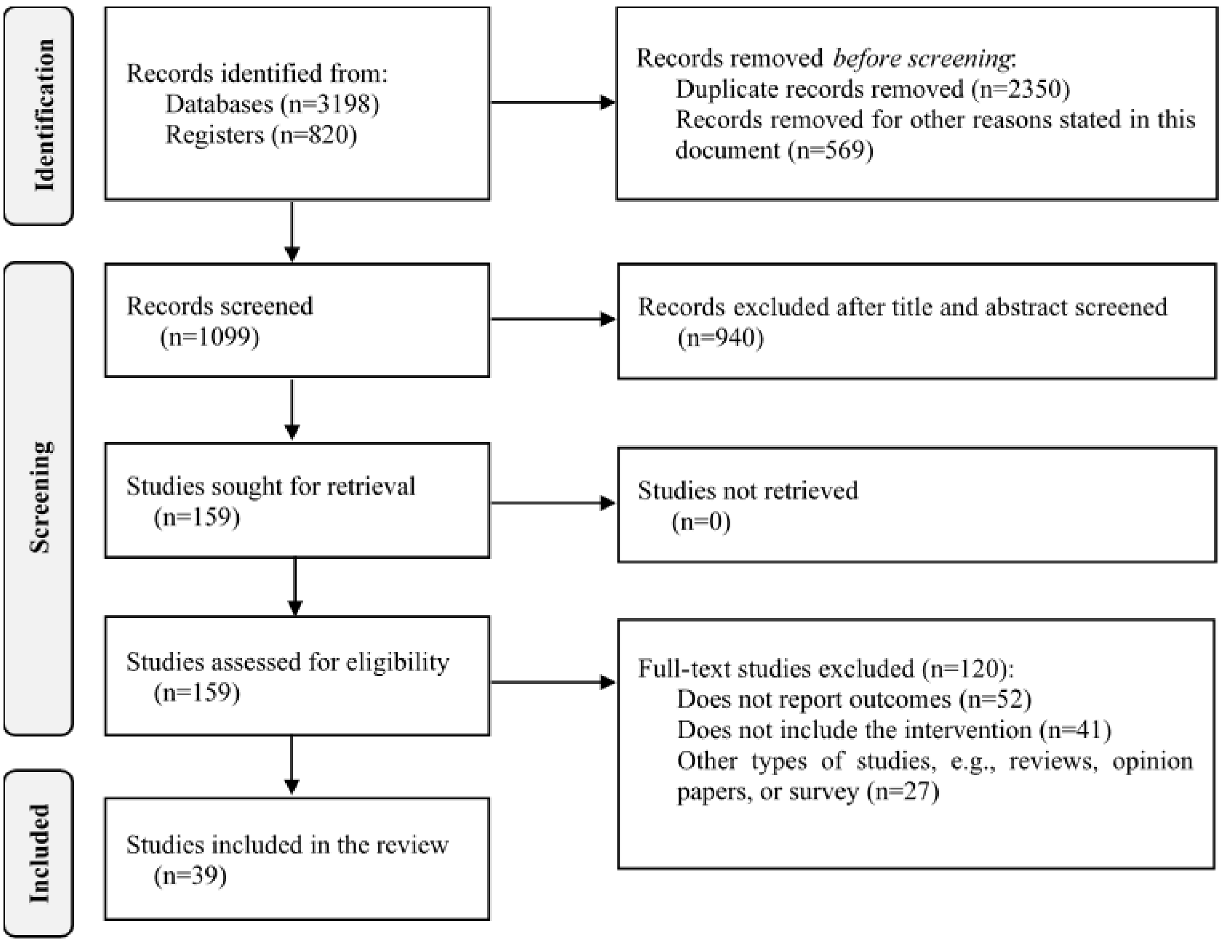

Figure 1. PRISMA flow chart based on Table 1.

We searched for interventions reporting outcomes described as patient outcomes, quality of care, utilization or access to services, and resource use by the EPOC Group [109] which were also utilized in previous studies [128–130]. Patient outcomes relate to health status, such as infection rate or mortality rate. Quality of care outcomes were: (i) readmission rate, the percentage of patients readmitted to a hospital after a previous hospital stay; and (ii) adherence to recommended guidelines or practices. Outcomes related to utilization of services were: (i) length of stay (LOS) for outpatient, which is the time a patient spends going from admission to discharge; (ii) length of stay for inpatient, which is the time a patient spends from occupying a bed until being discharge from the hospital; (iii) turnover time (TOT), the time lapse between fulfilling one patient's care and beginning another patient's care; and (iv) turnaround time (TAT), the time it takes to begin a procedure after the previous procedure has been completed. Access to service outcomes were: (i) boarding time, the time it takes to be assigned a hospital bed after being admitted; (ii) waiting time, the time a patient spends waiting for a consultation by a health professional; (iii) number of patients who left without being seen (LWBS); and (iv) the time spent waiting for an appointment. We also included patient and staff satisfaction as secondary outcomes, both measured as an average satisfaction score with validated instruments such as the HCAHPS survey [131], the Patient Satisfaction Questionnaire (PSQ-III), or the Picker Patient Experience Questionnaire (PPE-15). Table 1 depicts the systematic review framework including inclusion and exclusion criteria.

Table 1. Systematic review framework.

Process	Criteria	Description
Search strategy	Data sources	• PubMed-Medline, Cochrane Library, Ebsco-Host, Web of Science, and Scopus • Google Scholar
Selection of studies	Studies	• Published studies in English up to July 2022
	Participants	• Hospitals (inpatient and outpatient) with primary to quaternary care • Public and private
	Intervention	• Lean methodologies, six sigma, and similar interventions • Simulation (discrete event simulation, system dynamic simulation, agent-based simulation, and Monte Carlo simulation)
	Comparator	• Effect measures (mean, median, or percentages) of pre- vs. post-intervention or control group vs. intervention group
	Outcomes	• Patient outcomes, quality of care, utilization and access to service, resource use, patient and staff satisfaction
	Study design	• Randomized control trials (RCT), controlled before-after, pre-post, case-control, and cohort
	Exclusion criteria	• Surveys, reviews, opinion papers, technical notes, interviews, and editorial letters • Studies published in languages other than English • Studies that did not include a patient-oriented or direct healthcare service (e.g., suppliers' efficiency, administrative staff efficiency, medical device efficiency, efficiency of a medical device manufacturing company) • Studies without abstract and data
Data extraction and synthesis	Review processExtracted data	• Two reviewers screened, assessed, and extracted data. A third reviewer assessed when consensus was necessary • Study's location, settings, duration, aims, design, participants, intervention, comparator, outcomes, findings, and control conditions
Risk of bias	Tool	• Cochrane Risk of Bias In Non-randomized Studies of Interventions (ROBINS-I)

3.3. Data Analysis, Synthesis, and Risk of Bias

Three independent reviewers were tasked to evaluate the studies. Two of the reviewers screened the title, abstract, and keywords from each study to classify the contribution and to determine eligibility for an in-depth further evaluation. In case of disagreement (approximately 7%), the third reviewer intervened to reach a consensus. For inclusion and exclusion criteria, two reviewers evaluated the complete text of pertinent studies. In cases where consensus was not reached, a third reviewer evaluated these studies (around 4% of the cases). One reviewer focused on extracting data from articles and a second reviewer verified the data. As in similar studies [128,129], we extracted data defined in Table 1. The screening, evaluation, and extraction activities were performed manually by using reference manager software and spreadsheet software. Finally, we tabulated all data by using standardized forms. Due to the heterogeneity in studies and the lack of RCTs, results could not be pooled to perform a meta-analysis. Therefore, following similar approaches [46,47,51], we conducted a descriptive synthesis of the results, and summarized the findings of the main outcomes by utilizing the reported effect measures in each study (percentages, medians, or means).

All included studies were observational. Therefore, we assessed the risk of bias by using Cochrane's tool ROBINS-I (Risk Of Bias In Non-randomized Studies of Interventions) [132,133], which comprised seven bias domains within the judgment criteria, each with five levels (no information, critical, serious, moderate, and low) [132]. Two independent reviewers assessed each study following the ROBINS-I algorithm. To reach an overall risk of bias judgment, a third reviewer assessed a study when a difference existed up to obtain consensus.

4. Results

The process for identification, screening, and inclusion or exclusion of studies is depicted in Figure 1. Particularly, the search in the databases produced 4018 titles. The process of removing duplicates and studies that did not meet the inclusion criteria yielded 1099 studies for screening. Applying the exclusion criteria identified 940 studies for removal, resulting in 159 studies for eligibility. As a result of the full-text review, 120 studies were removed and the remaining 39 studies were considered in this research.

In this review we identified 39 studies that utilized an improvement approach (LSS) and a simulation paradigm in a healthcare setting. Derived from this dual intervention, the studies reported 73 different outcomes including LOS, 16; TAT, 14; waiting time, 21; TOT, 3, LWBS, 2; and wait time for appointment, 2. Additional outcomes included savings and earnings, 3; walking distance, 2; capacity, 2; and others, 8. On the other hand, no studies reported values of secondary outcomes such as patient satisfaction and staff satisfaction. Figure 2 shows the types of outcomes reported in the dual interventions.

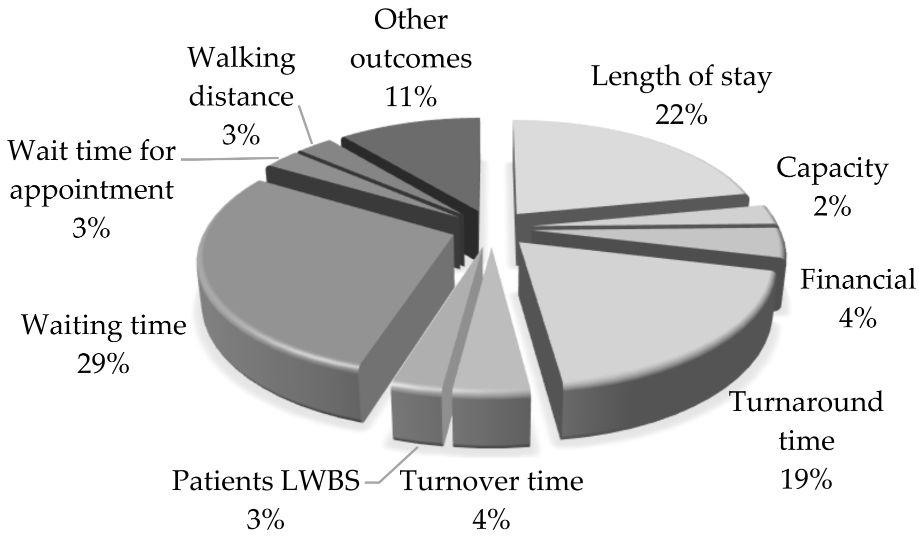

Figure 2. Type of outcomes reported after the dual interventions.

One of the most frequent measures after the interventions was the TAT, resulting in a reduction in all 14 outcomes in the 13 reported studies. Settings included ED, laboratories, OR, ambulance service, or medical record processing. Ten lean and simulation studies led to an average reduction of 30% in TAT, while three studies using LSS and simulation led to an average reduction of 56% in TAT. DES was the main simulation approach for TAT improvement reported in nine studies leading to a reduction of 34% on average. Table 2 shows all TAT outcomes and, when available, descriptions and statistics from the studies.

Twelve studies reported 16 outcomes associated with patients' length of stay (LOS), 14 out of 16 presenting a decrease after the dual intervention (see Table 3). Conversely, one study reported two outcomes showing no change and an increased in LOS after the intervention [41]. The most frequent setting for interventions focusing on LOS was ED with 10 out of 12 studies.

Table 2. TAT outcomes of the dual interventions.

First Author, Year; Country	Setting; Study Design; n; Time Frame	Main Intervention	Outcomes	Summary of Findings	Software; Simulation or Implementation
Indrawati, 2022; Indonesia [134]	Clinic; case study; n = 96	Lean and DES	Mean Lead time	Reduced from 6398 s to 3084 s	FlexSim; Simulation
Lokesh, 2020; India [135]	Pediatric emergency; case study; n = 44; 1 mo	LSS and DES	Mean TAT of tests	Reduced from 69 min to 36 min	Arena; Simulation
Noto, 2020; Italy [27]	Ambulatory care; case study; pre-post; n = 5	Lean and SD	Mean time of the process	Reduced from 92 min to 65 min	Not Specified; Simulation
Agnetis, 2019; Italy [136]	Hematological center; case study; n = 49	Lean and DES	Mean patient lead time	Reduced from 1165.8 min to 747.4 min	Arena; Simulation
Garza-Reyes, 2019; UK [67]	Ambulance service; case study; n = 850 ambulances; 1 mo	Lean, simulation (not specified), internet-based technologies, and GPS tracking devices.	Mean ambulance cycle time	Reduced from 124.9 min to 75.8 min	ProModel; Simulation
Ortiz, 2017; Colombia [137]	Internal medicine; case study; pre-post	Lean and DES	Mean lead time	Reduced from 9.9 days to 7.6 days	Arena; Simulation
Salam, 2016; Thailand [138]	Medical center; case study; pre-post	Lean and DES	Mean cycle time	Reduced from 5.8 h to 3.8 h	I-Grafx; Simulation
Haddad, 2016; Lebanon [70]	Radiology department; case study; n = 6	Lean and DES	Mean total patient time in the system	Reduced from 98.1 min to 15.9 min	Arena; Simulation
Bhat, 2016; India [139]	Medical record department; case study; pre-post; n = 100; 2 mo	LSS and simulation (not specified)	Mean TAT	Reduced from 19 min to 8 min	Arena; Simulation
Hirisatja, 2014; Thailand [140]	Out-patient surgery department; case study	Lean and DES	Mean TAT with appointment	Reduced from 144.2 min to 114.5 min	Arena; Simulation
			Mean TAT without appointment	Reduced from 178.2 min to 152.5 min	
Bhat, 2014a; India [141]	Out-patient department, case study; n = 56; 2 mo	LSS and DES	Mean cycle time and Standard Deviation	Reduced from 4.27 min to 1.5 min	Arena; Implementation
Kim, 2007; USA [142]	Radiation oncology department; case study; n = 6 mo	Lean and Simulation (not specified)	Mean Process time	Reduced from 290 min to 225 min	Not Specified; Simulation
Nelson-Peterson, 2007; USA [143]	Telemetry unit on hospital; time-series, pre-post; n = 8; 5 mo	Lean and Simulation (not specified)	Mean Registered nurse lead time	Reduced from 240 min to 126 min	Not Specified; Simulation

Note. DES indicates Discrete-Event Simulation; GPS, global position system; LSS, lean six sigma; min, minutes; mo, months; TAT, turnaround time; s, seconds.

Table 3. LOS outcomes of the dual interventions.

First Author, Year; Country	Setting; Study Design; n; Time Frame	Main Intervention	Outcomes	Summary of Findings	Software; Simulation or Implementation
Romano, 2022; Italy [35]	ICU; case study; n = 112	Lean and DES	Mean LOS	Reduced from 8.5 days/patient to 7.5 days/patient	PowerSim; simulation
Gabriel 2020; Brazil [37]	ED; case study; 12 mo	LSS and DES	Mean LOS	Reduced from 2213.7 min to 461.2 min	FlexSim; simulation
Ajdari 2017; USA [144]	ED; case study; pre-post; n = 56	Lean and DES	Mean LOS	Reduced from 69.75 min to 57.43 min	Simio; simulation
Dogan, 2016; Turkey [68]	Rehabilitation at public hospital; case study; n = 625,168	Lean and SD	Mean LOS	Reduced from 13,790 min to 11,558 min	Arena; simulation
Joshi, 2016; USA [145]	ED; case study; n = 200	Lean and DES	Mean LOS: patients stay for test results and prescription	Reduced from 128 min to 119 min	Arena; simulation
			Mean LOS: patients need only prescription	Reduced from 59 min to 42 min	
Lee, 2015; USA [7]	Emergency care center; case study; n = 18,726; 9 mo	Lean, ABS, machine learning, simulation, optimization	Mean overall LOS	Reduced from 10.5 h to 7.1 h	Real Opt; simulation
Lo, 2015; USA [41]	Pediatric ED; pre-post; 7 mo	Lean, DES, real-time voice recognition system, simulation, and electronic charting	Mean discharged patients LOS	Increased from 161 min to 168 min	Dragon; implementation
			Mean LOS	No change (270 min)	
Converso, 2015; Italy [69]	ED; case study	Lean and SD	Mean residence time	Reduced from 6 days to 5 days	PowerSim; simulation
Rutman, 2015; [76] USA	ED; pre-post; n = 98; 7 mo	Lean, and in situ simulation and EMR	Mean LOS in ED	Reduced by 30 min	Not apply (in situ); simulation
Tejedor-Panchon, 2014; Spain [146]	ED; case study; pre-post; n = 256,628; 36 mo	Lean, DES, and digital technology in X-ray	Mean LOS in ED (time spent in the examination area)	Reduced from 80.4 min to 61.6 min ($p < 0.001$)	I-Grafx, implementation
			Mean LOS in TC	Reduced from 137.8 min to 123.8 min ($p < 0.05$)	
			Mean LOS in MSC	Reduced from 219.7 min to 209.3 min ($p = 0.108$)	
Rosmulder, 2011; The Netherlands [147]	ED; case study; n = 704, 24 mo	Lean and DES	Mean LOS	Reduced from 97 min to 83 min ($p = 0.05$)	Tecnomatix; simulation
Mandahawi, 2010; Jordan [148]	ED; case study; n = 163	SS and DES	Mean LOS	Reduced from 84.49 min to 55.50 min	ProModel; simulation

Note. ABS indicates agent-based simulation; ED, emergency department; EMR, electronic medical records; h, hours; ICU, Intensive Care Units; LSS, lean six sigma; LOS, length of stay; MSC, medical-surgical cases; min, minutes; mo, months; SS, six sigma; TC, trauma cases.

Concerning waiting times, 18 studies reported improvements in all 21 outcomes (see Table 4). The main setting where the interventions took place was the ED with eight studies reporting an average reduction of 62%. Oncology department [9,142] and registration and information department [149,150] followed with two studies each.

Table 4. Waiting time outcomes of the dual interventions.

First Author, Year; Country	Setting; Study Design; n; Time Frame	Main Intervention	Outcomes	Summary of Findings	Software; Simulation or Implementation
Noto, 2020; Italy [27]	Ambulatory care; case study; pre-post; n = 5	Lean and SD	Mean waiting time for patients to be registered	Reduced from 8 min to 1 min	Not specified; simulation
Rahul 2020; India [38]	ED; case study; n = 190; 1 mo	LSS and DES	Mean waiting time	Reduced 76 min to 22 min	Arena; simulation
Ortiz-Barrios, 2020; Colombia [39]	ED; case study; n = 16,741; 15 mo	Lean, DES and virtual modelling	Mean waiting time	Reduced from 201.6 min to 103.1 min	Minitab; simulation
Bhosekar, 2021; USA [36]	OR, case study, 24 mo	Lean (just-in-time) and DES	Mean delay in surgery	Reduced from 31.2 min to 1.4 min	Arena; simulation
Al-Zain, 2018; Kuwait [40]	Obstetrics and gynecology; case study; n = 168	LSS and DES	Mean waiting time for appointment patients	Reduced from 59.8 min to 19.8 min	Arena; simulation
Baril, 2016; [9] Canada	Hematology–oncology clinic; case study; 10 mo, 2 mo of follow up	Lean, DES, and business game-virtual environment	Mean patient waiting time before treatment	Reduced from 61 min to 16 min	Arena; simulation
Joshi, 2016; USA [145]	ED; case study; n = 200	Lean and DES	Mean waiting Time	Reduced from 31 min to 8.3 min	Arena; simulation
Converso, 2015; Italy [69]	ED; case study	Lean and SD	Mean waiting for the surgery (max)	Reduced from 450 min to 354 min	PowerSim; simulation
Rutman, 2015; [76] USA	ED; case study; pre-post; n = 98; 7 mo	Lean, in situ simulation, and electronic medical records	Median time to see a provider	Reduced from 43 min to 7 min	Not apply (in situ); simulation
			Percentage of patients seen within 30 min	Increased from 33% to 93%	
Lin, 2014; Singapore [66]	Eye clinic; case study	LSS and DES	Mean patient waiting time	Reduced from 135.6 min to 103.5 min	FlexSim; simulation
Tejedor-Panchon, 2014 Spain [146]	ED; case study; pre-post study; n = 256,628; 36 mo	Lean, DES, and digital technology in X-ray	Mean wait time to see a physician	Reduced from 58 min to 49.1 min ($p < 0.001$)	I-Grafx; implementation
Hirisatja, 2014; Thailand [140]	Out-patient surgery department; case study	Lean and DES	Mean waiting time with appointment	Reduced from 89.2 min to 74.7 min	Arena; simulation
			Mean waiting time without appointment	Reduced from 120.5 min to 106.1 min	
Bhat, 2014b; India [149]	Health information department; case study; n = 224	LSS and DES	Mean waiting time in the system	Reduced from 21.1 min to 1.1 min	Arena; simulation
Bhat 2014a; India [141]	Out-patient department; case study; n = 56; 2 mo	LSS and DES	Mean waiting time in the system	Reduced from 32 min to 1 min	Arena, implementation
Mandahawi, 2010; Jordan [148]	ED; case study; n = 163	SS and DES	Mean patient waiting time	Reduced from 33.2 min to 12.9 min	ProModel; simulation

Table 4. *Cont.*

First Author, Year; Country	Setting; Study Design; n; Time Frame	Main Intervention	Outcomes	Summary of Findings	Software; Simulation or Implementation
Khurma, 2008; Canada [151]	ED; case study; 1 mo	Lean and DES	Mean waiting time in 1st shift	Reduced from 226.9 min to 4.9 min	ProModel; simulation
			Mean waiting time in 2nd shift	Reduced from 124 min to 9.1 min	
Yu, 2008; USA [150]	Registration department; case study; n = 362; 3 mo	Lean six sigma and DES	Mean waiting time	Reduced from 42.3 min to 6.5 min	Arena; simulation
Kim, 2007; USA [142]	Radiation oncology department; case study; n = 6 mo	Lean and simulation (not specified)	Mean waiting time of treatments initiated	Reduced from 7 days to 1 day	Not specified; simulation

Note: DES indicates discrete event simulation; ED, emergency department; LSS, lean six sigma; min, minutes; mo, months; SD, system dynamics; SS, six sigma.

Although TOT has been reported in previous studies as a frequent measure [12,129], we found only two studies reporting a reduction in three TOT outcomes. Both studies utilized lean and simulation in OR [152] or in a general hospital [143]. Similarly, two studies measured the percentage of LWBS with both reporting improvement after the intervention. One study [7] utilized lean, simulation and machine learning to reduce by 30% the number of patients LWBS in an emergency care setting, while the other [146] reduced the percentage of patients LWBS from 2.8% to 2%.

We did not identify any patient health outcomes such as health status and wellbeing. Only one outcome categorized as quality of care was identified, being a reduction in the percentage of 30-day readmission rate [7]. No other related outcomes were identified, including the adherence to recommended practice, mortality rate, boarding time, social outcomes, and on-time starts in the OR. However, we did find additional outcomes related to resource use and access to services such as the increase in cataract surgery capacity and productivity [153], reductions in waiting time for an appointment [65], the improvement of staff walking distance and nurse lead time [143], a reduction in the inventory of medical records processed [139], a reduction in mean patients in queue in the registration process of a hospital [149], a reduction in the percentage of scheduled staff utilization [149], an increase in the percentage of patients seen within 30 minutes [76], and a reduction in steps needed to initiate radiation therapy [142]. Moreover, only three studies reported values related to savings [7,105,152]. Surprisingly, no study provided results of either patient or staff satisfaction after the intervention. Table S3 of the Supplementary Materials summarizes all outcomes and findings of the considered studies.

Regarding the types of intervention (see Figure 3), 26 studies utilized lean and simulation (67%), 11 studies used the LSS and simulation approach (28%), while the remaining two studies employed six sigma and simulation. In regards to the research scope, all interventions were limited to individual departments or processes and did not occur throughout the organization. Regarding risk of bias, Table S4 of the Supplementary Material depicts the assessments of the studies. Four interventions were assessed with low bias, 33 with moderate bias, and two with serious bias.

Regarding simulation, the DES paradigm is reported in 29 out of 39 studies (74%), SD was applied with lean in three studies, and the ABS simulation is presented in one implementation in conjunction with lean. Two studies reported other simulation approaches while four studies did not report the type of simulation used. Figure 3 shows these results. Particularly, DES was utilized along with lean in 17 studies, ten studies applied with LSS, and the remaining two studies with SS. The most used software in the DES application is by far the Arena software with 15 studies reporting it, FlexSim with three studies, and ProModel with two. The remaining were only reported once in papers (I-Grafx, Simio, Simul8, PowerSim, Dragon, Tecnomatix, and Minitab). Particularly, the most used software for SD was Arena and Promodel; The software used for ABS was RealOpt. In other cases, no software was used for the simulation of scenarios. Instead, the techniques of in situ [76] and role-playing [154] were used, which consisted of simulating the scenarios and roles of the personnel involved by people actually participating in the process in order to determine possible improvements.

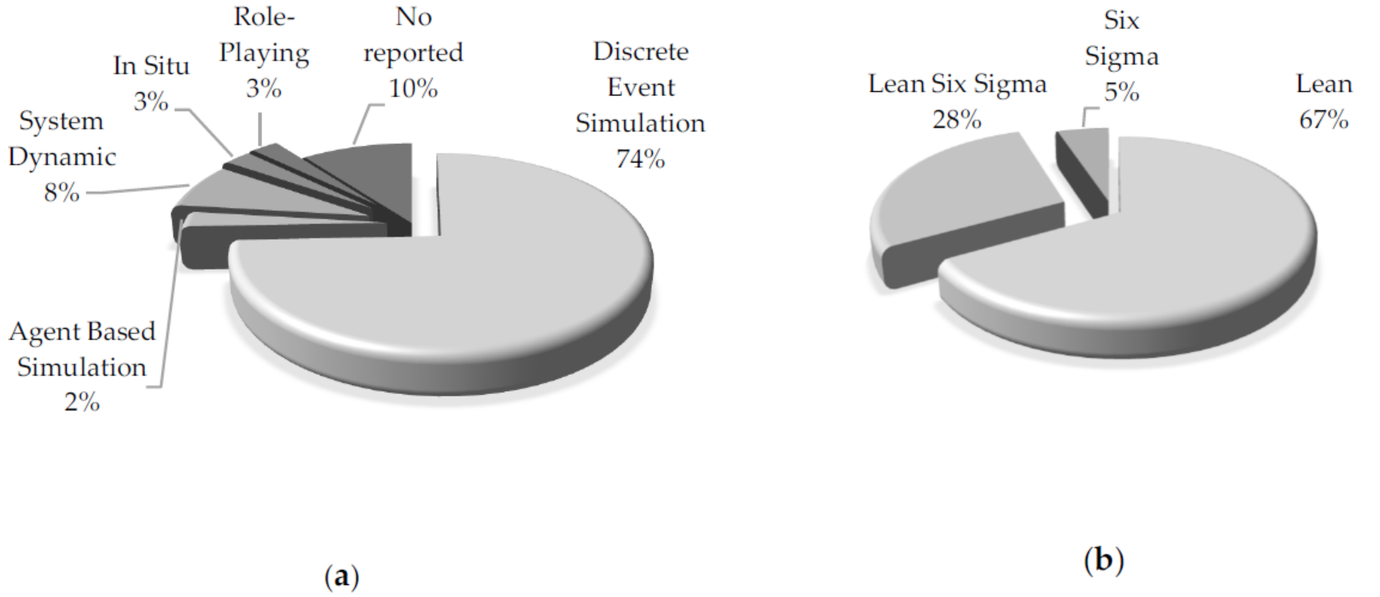

Figure 3. The types of simulation and improvement approaches that supported the dual interventions are summarized by: (**a**) types of simulation in dual interventions; (**b**) main improvement approaches in dual interventions.

The most recurrent setting for interventions was ED reported in 14 studies. The country with the largest number of interventions was the United States (ten studies), similar to the results of previous studies [128,129]. This also supports the findings that a great number of American hospitals have implemented lean and similar interventions, between 54% [155] and 70% [156]. Other countries were Italy with six studies and India with five studies.

5. Discussion

5.1. Effects of LSS and Simulation on Healthcare Services

According to our results, interventions of improvement approaches such as LSS along with simulation impacted up to 15 different types of outcomes, with the three most representative being LOS, waiting time, and TAT. Less frequent outcomes included turnover time, number of patients who left without been seeing (LWBS), walking distance, and savings. Of the 73 outcomes reported, 71 showed improvements after the interventions. Therefore, in regards to the RQ1, the findings suggest that the interventions had a positive effect on outcomes mainly related to patient flow, that is, improvements related to utilization, coverage, or access to healthcare services. In addition, there was a positive effect on outcomes related to resource use (human resources, buildings, equipment, or consumables). Regrettably, we did not identify outcomes for patients concerning health status, adherence to recommended practice, or safety. Moreover, despite the fact that several studies indicated that improvements might impact patient and staff satisfaction [40,65,140,144,146,148,150,151], none of the studies reported findings to support this claim. Additional expected outcomes included those related to cost reduction. Despite the fact that simulation [26,157], and six sigma [158] are related to savings, and that lean interventions are linked to less Medicare spending per beneficiary in the United States [155], few interventions included reports regarding savings or cost reductions [7,105,152]. The scarcity of cost outcomes aligns with the difficulty to associate lean and financial benefits [130] and this is compounded by hospitals' inability to translate benefits into economic data [128]. Multidisciplinary teams including management, financial, and accounting staff could reduce this deficiency.

5.2. Dual Interventions of LSS and Simulation in Healthcare Services

Dual interventions vary from study to study. However, successful interventions of improvement approaches such as LSS along with simulation require a clear understanding of the operational performance [159] goals to be pursued, which in healthcare are expanded also to error-free delivery of care [160], meeting the demand [93], and in general improving the value of care [161]. In regards to the RQ2, the findings suggest two general approaches.

Interventions following the DMAIC methodology initiate a process flow visualization in the early stages, aiming at obtaining a diagnosis of the current situation. Here, due to the focus on visualizing the flow of people, material, and information, the VSM was identified as the main tool to support the creation of such a current state [65,66,135], to eliminate possible obstacles at the moment of cooperating, and to reduce the gap between the current and desired performance [137]. Then, simulations of future scenarios are developed in the analysis and improvement stages [65,66,135,150]. In this way, VSM provides insightful data from the process, e.g., cycle time, which is then used as an input for simulating possible changes and scenarios [134]. Afterwards, simulation is also used for both objectives, evaluation [154] and validation [139].

Interventions not following the DMAIC methodology start by reviewing and analyzing processes. Particularly workflow analysis, which is an initial step in simulation, couples with tools such as the VSM and the lean focus on flow analysis. VSM, which supports both lean and simulation extensively [12,162], aids to visualize the time-line that the user spends on each healthcare process, including value added time, i.e., when the patient receives effective assistance, and non-value added time, when the patient is just waiting [146]. This visualization might be used to model the patient flow using simulation for current and future state maps [68]. Therefore, VSM is a good starting point since it depicts the stream of processes from the customer's point of view [70]; however, it must be taken into account that conventional VSM does not specifically represent variability [163]. In fact, simulations are needed to model complex healthcare value streams such as patient queues [134]. Therefore, the optimization of VSM is a typical multiple-attribute decision-making (MADM) problem that involves the evaluation of multiple performance metrics such as inventory levels, lead times, and service levels [164].

5.3. Simulation Paradigms Utilized in the Interventions

In regards to the RQ3, our results indicate that 74% of the interventions employed DES as its simulation approach. This result supports the finding that DES continues to be the most popular approach in healthcare [135,152], indicating its pervasiveness across several types of problems related to scheduling and optimization. System dynamics (SD) [27,67,68] and agent-based simulation (ABS) [7] were utilized less frequently in the interventions. The popularity of DES in healthcare is a result of healthcare entailing stochastic systems and dynamic process; thus DES facilitates the modeling and flow analysis in such processes [56]. In addition, the use of DES provides several benefits for modelling hospitals including the flexibility for scale changes, the level of detail, the individual patient focus, the inclusion of stochastic factors affecting the system, the ease in changing the model's components, the analysis of waiting time and queues, and the visual representation of patient flows [55,165]. Thus, by simulating individuals through a system, these models are more understandable and more closely resemble reality [56]. In regard to SD, this paradigm also provided robust methodological support to a flow analysis and the use of tools such as VSM, due mainly to its systemic view, explicit link between system structure and behavior, and effective visual representation [27]. SD is principally used at more strategic levels in order to gain insight into the relations between the different parts of the healthcare system [166]. We only identified three interventions using SD [27,67,68]. The scarce use of SD with improvement approaches is associated with the notion that SD models are less powerful in capturing the level of granularity and less flexible in modeling individual entities of the system [166]. A helpful tool to decide whether SD is an appropriate method for modeling the effects of a specific intervention on a healthcare system includes a checklist [4].

On the other hand, ABS is more focused on modelling autonomous individual agents with their complex interactions [167]. Different ABS has been developed in healthcare [168,169], demonstrating its ability to understand social systems in which individual agents (e.g., doctors and nurses) might differ in behavior. Although few interventions of ABS along with lean or six sigma exist, the applicability of this dual intervention in healthcare seems promising as more attention is required for patient and staff interactions. Despite the fact that Monte Carlo (MC) simulation has been used on its own in different healthcare settings [170,171], we did not find a dual intervention of MC and improvement approaches.

Regarding software, Arena stands out as the most recurrent software when simulating along with improvement approaches. This software was used in 43% of the studies, consistent with what previous studies found [55,64] on account of its suitability to address a variety of problems in healthcare. Both the validation of a value stream map [139] and the simulation-optimization approach by employing the opt-quest function [36] stand out as recurrent approaches of Arena.

The use of simulation among the 39 studies can be summarized by two tactics: (i) practical interventions simulating various scenarios followed by the implementation of the best solution in the healthcare setting, and (ii) hypothetical interventions which combine lean or six sigma, or both, to simulate scenarios with potential best solutions, but not reporting the implementation.

5.4. LSS Tools Utilized in the Interventions

In regards to the RQ4, our findings indicate that VSM was utilized in 19 studies being the most frequent tool. An Ishikawa diagram was reported in eight studies, a process flow chart in eight studies, and the 5′S program in five studies. Other less reported tools included Kaizen, just in time, Kanban, and single minute exchange of die (SMED).

Eleven studies followed the DMAIC approach. Interestingly, few statistical tools were reported, ANOVA being an example [65,149,150]. Other less reported tools included process capability, regressions, and design of experiments (DOE). In fact, DOE has been reported as one of the main tools within six sigma [172]; however, in this research, only one study reported the DOE utilization [37]. This absence might be due to simulation replacing trials in processes where real experimentation is difficult. Thus, the cost of an improvement project involving six sigma can be significantly reduced if DES can be adopted to provide results regarding different process configurations [105].

The benefits of VSM included the facilitation to visualize all of the steps involved in the work [142] including physical system, processes and interconnections [137] as well as to determine "process time" (i.e., the actual time it takes to complete an activity) [142].

5.5. Complementary Role of Simulation and LSS in the Interventions

This subsection addresses the RQ5. According to our results, to improve patient flow outcomes, interventions of improvement approaches (LSS) along with simulation focus on either flow problems or problems concerning allocation of resources. Indeed, simulation in healthcare focuses mainly on the scheduling or the flow of patients and resources in the system [64].

For scheduling problems with patients or resources, the dual intervention supports process re-engineering resulting in a pull strategy for appointment management instead of a push strategy for patient management. We identified that most of the interventions relied on simulation and lean. However, in addition to lean and simulation, mathematical optimization served to shift from a push strategy for patient management to a pull strategy for appointment management leading to a reduction in patient lead time in an appointment scheduling of hematological treatments [136]. In this regard, one primary cause of queuing is the mismatch between demand and capacity [173]. Variations in demand and capacity can be analyzed using optimization tools and tools related to six sigma.

Simulation stands out as a recurrent approach to use in healthcare to analyze processes, assess changes, and evaluate possible effects prior to their actual implementation. Therefore, LSS benefit from the scenarios and changes and the evaluation and validation that simulation provides, leading to the timely identification of best improvement proposals and avoiding expenses, time and other resources wasted. Conversely, simulation benefits from the structured approach of LSS to gather data and solving efficiency and variation problems. Thus, the dual intervention serves as a foundation for streamlining patient, material, and information flow and stabilizing processes. Among the interventions, we identified additional Industry 4.0 technology including machine learning [7], digitalization [146], automatization [41,138], and internet-based tools [67].

The variety of tools and techniques that might be utilized when conducting the dual intervention as well as the processes complexity, require correspondent expertise, thus, the need for multidisciplinary teams is inherent. Such teams enhance a global vision of the healthcare process allowing for more expedient identification of problems and allowing for consensual decisions and shared results. These also facilitate the clarification of responsibility throughout the process [146]. We found that 34 out of 39 studies indeed reported the creation of multidisciplinary teams, involving nurses, doctors, and personnel from various areas. Engineers [136], and external advisors [40], were also identified among the studies. Particularly in situ simulations, where actual people simulate scenarios, the inclusion of physicians, nurses, and facilities personnel supported a successful redesigning of a resuscitation room [76]. To obtain a complete understanding of the healthcare process, stakeholders need to be involved, including all fields from engineering, health sciences and education, health care delivery improvement, and health care technologies [174].

5.6. Effects on Patient and Staff Satisfaction

This subsection addresses the RQ5. Even though patient satisfaction leads process improvement initiatives in healthcare systems [175–177], we did not find evidence of improvements in patient satisfaction after the interventions. Similar to previous studies, interventions including lean focused mainly on flow and efficiency but overlooked patient satisfaction [128,129,178]. In addition, we anticipated that improvements in patient flow outcomes might also improve patient satisfaction. That is a reduction in terms of time in TAT, TOT, and walking distance might decrease waiting times for patients and staff, which might contribute to a reduction in LOS and the percentage of LWBS and, ultimately, might improve both patient and staff satisfaction. Despite this inherent relationship among outcomes, we did not find studies focusing on a cause-effect analysis. Other expected but unreported outcomes included staff satisfaction and wellbeing, which is surprising since the staff play a fundamental role in such interventions [179,180]. This absence highlights that we understand very little about how work conditions are changed [181] and emphasizes the need for analytical attention and technological solutions focused on minimizing the burden experienced by physicians and nurses [180]. Despite the fact that longer wait times decrease patient satisfaction scores [182], the absence of these measurements is consistent with the limited number of lean interventions that deliberately included sociotechnical aspects [183] and a non-significant association between lean adoption and patient outcomes or patient satisfaction [155]. Moreover, we did not find evidence of environmental or social outcomes among the interventions. Only one study [152] expressed concern particularly for the sustainability of public finances in healthcare; thus, sustainability is a challenge for future research.

5.7. Barriers and Challenges

The reviewed studies did not include feedback from patients and staff. Limited patient involvement [184] and staff participation have been identified to have little impact on the proposed interventions, thus representing a barrier, particularly, since a sustainable intervention depends on staff involvement and commitment.

A strong focus on patient and staff needs represents a challenge for future interventions. In this regard, patient and staff participation in the evaluation process of simulated scenarios of LSS interventions might also enhance satisfaction. Moreover, improvements obtained with LSS might be used to simulate patient and staff satisfaction. On this point, agent-based simulation provides this needed focus based on the ability to represent stakeholder behaviors, which have been identified as weaknesses of DES [55].

Moreover, considering that LSS interventions have been previously utilized to improve the health and wellbeing of patients in terms of reduction in readmissions [185], infection rates [186], or errors in medication [187]; we envision further interventions supported by simulation and other technologies. Regarding the reduction in infection rates, lean-six sigma allowed the identification of variables that influenced the risk of infections [186]. In these cases, simulation might be used to test different corrective actions prior to their actual implementation. Similarly, lean-six sigma allowed the determination of risk factors leading to errors in medication [187]; thus, by simulating new procedures for dispensing medications, the healthcare sector might assess several scenarios before changes are implemented.

Another important challenge is the quality, accessibility, and amount of data, which might dictate the possibilities to effectively conduct future interventions. Thus, the smartness of the system depends on data [174]. On one hand, the lack of operational data in the hospital environment makes process improvement very challenging [188]; however, as Industry 4.0 technologies permeate more healthcare processes, data availability might increase in quantity, quality, and timeliness. Sensors, tracking systems, IoT devices, and medical information systems might serve to increase data availability [12]. On the other hand, the expected increased amount of data is another challenge. Different technology including simulation, big data analytics [189,190], and AI [191] might offer support in the persistent task of analyzing root causes. Moreover, based on real-time data, the simulation model can automatically be adapted according to the modifications of the real system, enabling more efficient and effective decision making [192]. In fact, simulation serves to advance towards a more modern technology such as digital twins, recognized as the next modelling, simulation, and optimization paradigm [193,194]. Digital twins represents an opportunity for healthcare due to its ability to extend the use of simulation [193] to support the design [195] and redesign [196] of patient-centered healthcare settings; thus contributing to a holistic perspective to optimize the outcomes across the entire patient journey process instead of focusing only on departments.

Additional barriers identified included the lack of management involvement [197], cultural barriers, resource limitations [198], physicians' resistance to change [199–201], implementation cost, long learning curve, and technology incompatibility [202]; all of them are worth considering in future interventions.

Although only two interventions of six sigma and simulation were found [82,106], more interventions incorporating more advanced statistical tools along with data-acquisition technologies and simulation are expected. This combination has the possibility to create a solid analytical approach [55].

5.8. Study Limitations

The nature of our research presents some limitations. Most studies were observational pre-post designs and computer simulations. For this reason, the possibility of confounding variables and the absence of randomization did not allow us to determine cause-effect relationships between the interventions and the outcomes. Furthermore, differences in the handling of data (settings, the length of the studies, data collection procedure, and processing approaches) necessitate caution be observed to avoid generalizing the results of this research. Finally, the risk of bias and heterogeneity of studies prohibited us from performing a meta-analysis.

6. Conclusions

In light of the fast-rising use of dual interventions of simulation and improvement approaches such as lean or six sigma, this research outlines the main results obtained as well as the surrounding context of such interventions in order to provide insights for future research and similar interventions in healthcare.

As identified in our research, the interventions mainly led to positive effects on up to 15 different outcomes regarding patient flow. This indicates that the interventions focused mainly on problems related to the ease with which patients were able to access or utilize healthcare services, followed by problems related to the use of resources.

Regrettably, LSS and simulation interventions focus very little on reporting outcomes related to patient and staff health, wellbeing, and satisfaction, signaling a gap in the research. Increasing patient and staff participation in the evaluation process of simulated scenarios of LSS interventions as well as expanding the dual interventions on reducing infection rates or errors in medication might reduce this shortcoming.

Therefore, our findings confirm that dual interventions focus mainly on utilization and access to healthcare services, particularly on either patient flow problems or problems concerning the allocation of resources; however, most interventions lack evidence of implementation.

LSS complements simulations by providing a structured approach to analyze processes and to identify possible solutions to reduce or eliminate variations and activities that do not add value to patients and other stakeholders, such as doctors and nurses. Thus, simulations benefit from the problem-solving, data-driven, and team-oriented approach of LSS. Conversely, simulations complement LSS by providing answers to difficult questions without requiring the application of physical changes in a process or setting. Thus, LSS benefits from the evaluation and validation of scenarios that simulations provide. Therefore, this dual intervention allows hospital decision-makers to evaluate the pros and cons for each possible solution, leading to the timely identification of best improvement proposals. Thus, the dual intervention serves as a foundation for streamlining patient, material, and information flow and stabilizing processes. Despite the expected savings and efficient use of resources, little evidence was found to support financial benefits, indicating a pending area to be covered.

Lean clearly stands out as the main improvement approach in dual interventions followed by a combination of LSS. On the other hand, dual interventions relied mainly on discrete event simulation (DES) to create representations of a healthcare process and the consequent results in desired outcomes. Agent-based simulation (ABS) and system dynamics (SD) were less utilized among interventions.

However, due to a lack of patient and staff satisfaction outcomes being reported, we foresee an increased use of these paradigms along with more Industry 4.0 technologies in order to capture data and best represent behaviors in varying settings and contexts.

Finally, LSS along with simulation are complementary tools with distinct goals and different approaches, but their integration has the possibility to expand the results that were previously obtained without integration.

7. Future Research

In terms of future lines of research consequential to this study, we propose considering more LSS and simulation interventions along with using complementary technologies related to Industry 4.0, including those that collect and analyze data. The data-availability intensification might also introduce new approaches for those interventions including the use of digital twin and related technologies in even more healthcare settings, which seems to be closely-related research. Related to this suggestion, we envision studying the effects, enablers, and barriers in more complex interventions, as well as incorporating the impact of cultural, economic, and regional features.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/xxx/s1, Table S1: PRISMA Checklist. Table S2: search strategy; Table S3: extended summary of findings; Table S4: traffic light of the risk of bias assessment.

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