IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 20 May 2023, accepted 21 June 2023, date of publication 5 July 2023, date of current version 14 July 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3292119

RESEARCH ARTICLE

Leveraging Digital Twins for Healthcare Systems Engineering

NADER MOHAMED [1], (Member, IEEE), **JAMEELA AL-JAROODI** [2], (Member, IEEE), **IMAD JAWHAR** [3], (Member, IEEE), AND **NADER KESSERWAN** [2]
[1]Department of Computing and Engineering Technology, Pennsylvania Western University, California, PA 15419, USA
[2]Department of Engineering, Robert Morris University, Pittsburgh, PA 15108, USA
[3]Faculty of Engineering, Al Maaref University, Beirut 1600, Lebanon

Corresponding author: Nader Mohamed (mohamed@pennwest.edu)

ABSTRACT Healthcare systems are complex systems that need effective and efficient operations, optimizations, management, and control to offer reliable, high-quality, and cost-effective healthcare services. There are different approaches to improve the management of healthcare systems including utilizing the healthcare systems engineering principles. Healthcare systems engineering views a healthcare organization as a system and applies the engineering analysis and design principles to improve different aspects of healthcare services provided in that system. While this approach can provide many advantages for healthcare organizations, there are also many challenges hindering the ability of healthcare systems engineers from effectively accomplishing their mission. The initiation of the digital twin technology formed several potential methods for various industrial sectors to enhance their operations. Accordingly, they can help improve productivity, cost-effectiveness, reliability, quality, and flexibility. This paper studies how digital twins can be utilized for improving healthcare systems engineering processes and outcomes to enhance different aspects of healthcare systems. The paper discusses some of the challenges of healthcare systems engineering and how these challenges can be relaxed by utilizing digital twins. The paper also develops a conceptual framework to utilize digital twins for improving healthcare systems engineering processes and outcomes and discusses the prospects of such utilization on achieving the goals of healthcare systems engineering. In addition, the paper provides some discussions on the impact of this utilization and the future research and development projections of the employment of digital twins for healthcare systems engineering.

INDEX TERMS Digital twin, healthcare, healthcare systems engineering, simulation, systems engineering, systems modeling.

I. INTRODUCTION

Healthcare systems engineering is the application of systems engineering (SE) principles to the healthcare domains. Systems engineering employs systems thinking principles and values to deal with complex applications over their life cycles. These complex applications need careful and optimized design, development, implementation, and maintenance to be successfully deployed and operated. Systems engineering deals with the challenges in these complex applications such as requirements engineering, testability, dependability, reliability, maintainability, security, safety, and other management issues like logistics, teams, and resources management in such applications.

Healthcare systems engineering offers systems-based solutions and assists in managing operations and projects that focus on healthcare issues in a broad range of areas [1]. This includes areas related to healthcare resources such as healthcare human resources, facilities, supplies and equipment. It also manages and optimizes healthcare processes to achieve some important organizational goals such as improved quality, enhanced access to healthcare services, and increased competitive advantage.

Healthcare systems engineering provides numerous advantages for improving healthcare systems, yet, there are some obstacles facing the application of its vision and principles.

The associate editor coordinating the review of this manuscript and approving it for publication was Giovanni Merlino.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

These obstacles are due to the unavailability of advanced software tools that can help healthcare systems engineers achieve their roles. The unavailability of these advanced tools can extend the time needed to discover existing healthcare systems issues, and the time needed to understand these issues and identify their root causes. This will also make it harder to identify the right and applicable solutions to effectively solve these issues without causing negative impacts. In addition, for any healthcare system issue, multiple potential solutions may exist. However, it is difficult for healthcare systems engineers to evaluate and select the best solution without having the right tools to identify and compare the expected outcomes and impacts of these solutions. Many of the mentioned challenges and others can be resolved by using digital twins to enable the development of software tools that can assist healthcare systems engineers to effectively achieve their objectives.

There is high interest and motivation in utilizing digital twins for improving different industrial domains including healthcare systems [2], [3]. A digital twin is a digitalized description of a real-world's physical components, systems, or processes that offers a virtual representation to be employed to perform simulations, evaluations, optimizations, and testing virtually. These employments can provide effective, reliable, and rapid decisions about how to improve the operations of different physical worlds and industrial applications.

This paper examines the benefits of utilizing digital twins for improving the processes and outcomes of healthcare systems engineering. It develops and discusses a conceptual framework for utilizing digital twins for healthcare systems engineering. The opportunities and challenges of utilizing digital twins for healthcare systems engineering are also discussed. In addition, the paper discusses the impact and future research and development prospects employing digital twins for healthcare systems engineering. While many previous works investigated the benefits of digital twins for different applications in healthcare [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], none of them investigated the benefits of utilizing digital twins for healthcare systems engineering nor provided any frameworks for utilizing digital twins to improve the processes and outcomes of healthcare systems engineering.

The rest of the paper is organized as follows. Section II provides background information about healthcare systems engineering and digital twins and discusses related work on utilizing digital twins for healthcare. Section III discusses the challenges of healthcare systems engineering. Section IV develops a conceptual framework to utilize digital twins for healthcare systems engineering. Section V discusses the opportunities of utilizing digital twins for healthcare systems engineering. Section VI discusses the challenges of using digital twins for healthcare systems engineering. The potential impact of utilizing digital twins for improving healthcare systems engineering to achieve its goals and some future prospects are discussed in Section VII while Section VIII concludes the paper.

II. BACKGROUND AND RELATED WORK

This section offers some background information regarding healthcare systems engineering and digital twins then provides a brief discussion of some of the current related work covering the subject of utilizing digital twins for healthcare and healthcare systems.

A. HEALTHCARE SYSTEMS ENGINEERING

The complexity and size of healthcare providing organizations created the need to find ways to effectively and efficiently manage their facilities and services. Thus, the notion of viewing healthcare as a system and approaching its operations accordingly. Systems engineering offers methodologies and approaches based on sound engineering principles to organize and operate complex systems. One of its main roles is to identify the system's inputs and corresponding outputs and optimize the operations to minimize the costs of inputs and operations and maximize the outputs and their quality. As such, healthcare systems engineering is an area of research and study that concentrates on investigating and creating efficient, effective, high-quality, dependable, and cost-effective processes and systems for healthcare [12]. Healthcare systems engineers and researchers work to continuously resolve different issues in healthcare systems and enhance healthcare systems effectiveness, terminate healthcare and treatment mistakes, boost, and expand access to healthcare services, and advance the values of healthcare services [13].

Healthcare systems engineering is considered an interdisciplinary field that overlaps and utilizes concepts and knowledge from other disciplines such as engineering, management and finance, information technology and law in addition to the relevant healthcare fields. The main roles and functions of healthcare systems engineering include:

1. Creating vision, values, foundations, methods, tools, and practices to improve healthcare processes and systems.
2. Improving access to healthcare services for different types of patients.
3. Reducing healthcare services costs.
4. Examining various healthcare processes and systems to recommend constant improvements.
5. Investigating various healthcare associated workloads and workforce engagements to propose enhanced healthcare operations and consequences.
6. Enhancing the operations, utilization, usability, maintainability, and life of different medical equipment.
7. Improving the utilizations and effectiveness of healthcare facilities such as treatment and operating rooms.
8. Enhancing the reliability, effectiveness, management, and outcomes of different healthcare supply-chain processes and systems.
9. Working on decreasing inconvenience and difficulties on healthcare professionals by enhanced planning, effective management, and optimized resources utilization.

10. Enhancing the safety of different healthcare facilities, processes, and systems.
11. Working on detecting potential risks on healthcare processes and systems.
12. Performing different capacity planning for the future healthcare services' expansions needs.

All these functions help in achieving the main goals of healthcare systems engineering in:

1. Enhancing the quality of healthcare services,
2. Improving patients access to healthcare services,
3. Improving healthcare competitive advantage, and
4. Enhancing healthcare cost-effectiveness.

B. DIGITAL TWINS

A digital twin is a digitalized description of a real-world physical component, system, or process that offers a virtual representation that can be employed for performing simulations, evaluations, optimizations, and testing. Utilizing digital twins for enhancing several aspects of industrial processes has been progressing as an important methodology to assist different industry domains including the healthcare industry. The model and concept of the digital twin was originally proposed in public in 2002 by Grieves [14] in a manufacturing engineer conference.

Any digital twin model has two main elements. These elements are the physical element and the digital element. The physical element can be a complete physical system, physical product, or actual process. In addition, any digital twin has a connection that links both the physical and digital elements. The connection between the physical element and the digital one requires some information flows including flows for data acquired from physical sensors. These sensors can be part of the physical element and employed for the operation of the physical element, or they are attached to the physical element primarily for the digital twin objectives.

Innovations in sensor technologies and their applications in healthcare facilitate collecting rich information about different healthcare systems, products, facilities, and processes. These sensors can be medical equipment sensors, healthcare facilities' sensors, human body biosensors, software generated data, etc. This information can be analyzed and processed to create digital twins for different aspects in the healthcare industry [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]. The created digital twins can be utilized for improving the practices and outcomes of healthcare systems engineering thus enhancing different aspects of healthcare services. Generally, the digital twins' technology is considered one of the most important technologies that enable new visions in healthcare such as Healthcare 4.0 [26], [27], [28].

C. RELATED WORK

There have been some recent efforts to investigate utilizing digital twins for improving some aspects of healthcare services. Some of these investigate the general potentials, benefits, and challenges of utilizing digital twins for healthcare systems [2], [3], [4], [5]. For example, digital twins can be utilized to improve personalized healthcare services [6], [7], [8]. Feng et al. [37] created a personalized digital twin to support noninvasive precise pulmonary healthcare. Subramanian et al. [38] used the digital twin's concept to create a real-time emotion recognition system supporting personalized healthcare. Liu et al. [39] developed a cloud-based solution that utilized digital twins to provide improved elderly healthcare services. Elayan et al. [40] developed a smart context-aware healthcare approach that is supported by the digital twin's concept. This approach provides improved detection for healthcare risk issues such as heart conditions.

There have been other efforts investigating how to improve different operational aspects of digital twins designed for healthcare systems utilization. These aspects include utilizing simulation and data mining to improve the digital twins' utilization outcomes for healthcare systems [10] and improve software security for digital twins used for healthcare applications [11]. In addition, Madubuike and Anumba [9] studied utilizing digital twins for improving healthcare facilities management. The authors' focus was mainly on the civil engineering aspects of healthcare facilities to enhance preventive maintenance as well as other applications for improving the processes of healthcare facilities management. The authors also proposed a digital twins' systems architecture for such applications.

Although, there are some efforts in investigating utilizing digital twins for various healthcare applications, none of them address utilizing digital twins for healthcare systems engineering, which focuses on overarching goals to achieve such as enhancing patients' access to healthcare services, healthcare services and facilities quality, healthcare systems cost-effectiveness, and healthcare services competitive advantages.

III. CHALLENGES OF HEALTHCARE SYSTEMS ENGINEERING

There are several challenges facing healthcare systems engineers in performing their roles to achieve the goals of healthcare systems engineering. These challenges can be classified as technical and non-technical challenges and we will mainly focus on the technical challenges. To understand these challenges, we need first to understand the situations in which healthcare systems engineers work to achieve their goals.

The main goal of healthcare systems engineers can be abstracted in one question: "how to provide the best possible healthcare services for patients using limited healthcare resources". To answer this important question, it is required for healthcare systems engineering to apply advanced problem-solving approaches to find the right answers. The main steps of this approach are:

1. identifying current and persistent healthcare issues in the healthcare organization.

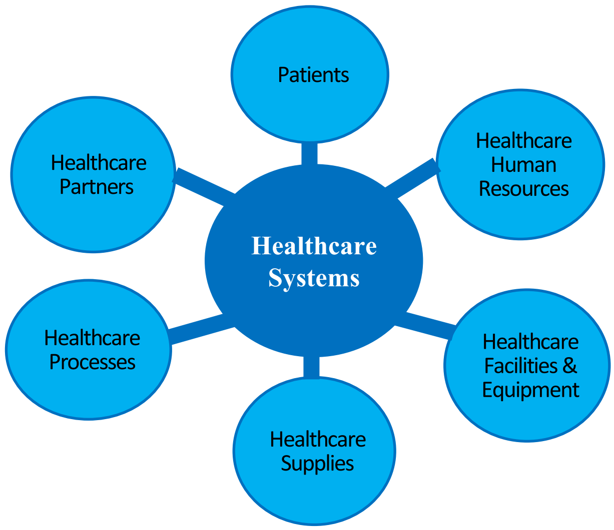


FIGURE 1. The main components of a healthcare system.

2. understanding the details of these healthcare issues and their root causes.
3. identifying different possible alternative solutions for these healthcare issues.
4. evaluating these alternative solutions to select the best ones to solve these healthcare issues.
5. investigating the details of the selected solutions and the best ways to implement them.
6. implementing and assessing the impact of the applied solutions on the healthcare organization and its operations.

There are many challenges in achieving these steps in a reasonable timeframe as healthcare systems are considered complex systems that are difficult to understand, evaluate and improve. There are many challenges in how to identify some healthcare issues, understand the details and root causes, identify different possible solutions and the best ones among them. All the steps of the advanced problem-solving approach require excellent capabilities to be achieved. These capabilities not only involve systems engineering approaches, but also advanced information technology solutions to augment and enrich the used systems engineering approaches. One of these information technology solutions that we are focusing on in this paper is the digital twins.

IV. CONCEPTUAL FRAMEWORK FOR UTILIZING DIGITAL TWINS FOR HEALTHCARE SYSTEMS ENGINEERING

Healthcare systems in terms of healthcare systems engineering can be viewed as six main component types as shown in Figure 1. These component types are patients, healthcare human resources, healthcare facilities and equipment, healthcare related supplies, healthcare processes, and healthcare partners. The patients' component includes different types of patients with different health histories and needs such as those with chronic diseases, disabilities, or temporary ailments.

The healthcare human resources include physicians and surgeons of all different specialties, nurses, laboratory technicians, operational staff, administrators, researchers to name some. The healthcare facilities can include hospitals and clinics, their treatment rooms, operating rooms, waiting rooms, laboratories, diagnostics rooms, storage rooms, and relevant offices. In addition, it includes all medical equipment, the IT infrastructure, and furniture.

Healthcare related supplies can be physical supplies or service supplies. Physical supplies can include medications, lab materials, cleaning supplies, treatment supplies, food, and other material and items needed for maintaining healthcare facilities and equipment. The service supplies are the essential services the healthcare systems receive from other partners to maintain their healthcare operations such as maintenance services on their medical equipment, catering services for staff, patients and visitors, energy, water, to name a few. Healthcare processes can include processes used for dealing with and treating patients, managing medical emergency situations, healthcare logistics processes, and other healthcare related processes. They also include procedures used for scheduling staff, monitoring inventory, managing the supply chain, streamlining workflow, and many other operational processes. The partners can include equipment and consumables suppliers, other hospitals, specialized healthcare centers, specialized medical laboratories, insurance companies, etc.

Digital twins can be created for all components of healthcare systems. Digital twins use data regarding healthcare facilities, processes, patients with different needs, supplies, and partners. They then compile in real-time the data supplied by the sensors, health information systems and other information sources to create digital matching elements. For example, digital counterparts can be created for all healthcare facilities including treatment rooms, operation rooms, waiting rooms, laboratories, diagnostics rooms, waiting rooms, etc. Digital counterparts can also be created for different healthcare processes such as treatment processes and logistic processes.

The most challenging digital twins for healthcare that need to be created are patient digital twins. Patient digital twins can be created to represent different patients with different personal characteristics such age, gender, health history, current health status, and healthcare needs. There are some works that investigated creating Patient digital twins. Okegbile et al. [8] investigated the key design requirements for creating patient digital twins. The authors also discussed some enabling technologies that can be used for creating such digital models and the technical challenges in that process.

Creating a digital twin for patients is the most complex as there are many levels of abstractions, various types of patients, numerous environmental factors, and continuous and rapid changes. Thus, patient digital twins can be created with different levels of details depending on their purpose. For example, they can be created to model fine grained health and environment information on individual patients to reflect the status of the individual in real-time. These can be used to support personalized medical services for the patients. Fortunately, this type of patient digital twins is not needed by most applications of healthcare systems engineering. Mostly, healthcare systems engineering requires an abstract view of patients' data that can support higher level decision making in healthcare systems to improve overall healthcare services efficiency, quality, access, and cost-effectiveness. Thus, it does not need to address or focus on individualized healthcare improvements. The applications of healthcare systems engineering need patients' digital twins with aggregated health characteristics and needs, which makes it easier to develop using mainly patients' information records available in the healthcare information systems.

The remaining components are less complex and can be generalized based on specific characteristics in each type. For example, when dealing with human resources, the person's individual traits will not matter, while it is important to have a good representation of their roles and skills. A digital twin for a nurse, for example, is abstracted to reflect their schedule, work location, specific skills and knowledge. Similarly, digital twins for facilities and equipment are relatively static and can be easily abstracted to the required level. Furthermore, changes in these components do not happen frequently and can be recorded and updated periodically or on a need basis.

Table 1 provides a summary of the different digital twins needed for healthcare systems engineering with some examples, and the main data sources to create them. The table only offers examples and is not comprehensive coverage. In addition, when considering the data sources, it is necessary to note that a digital twin of any type can benefit from all available data from all possible sources, thus the listed sources provide some of the essential sources.

Furthermore, when discussing the content of a digital twin, due to space limitation and the scope of this paper, we covered several important types of information that define the particular digital twin, but we acknowledge that there are a lot more information to be included for a digital twin. In general, the more information used in a digital twin the closer its representation of the actual component it mirrors will be.

A conceptual framework for utilizing digital twins for healthcare systems engineering is shown in Figure 2. In this framework, there is a digital twin creating system that is responsible for generating digital twins for the different physical aspects of a healthcare system. These digital twins are for all available healthcare facilities, equipment, healthcare human resources, supplies, processes, partners, and patients. This system receives two types of information. The first comes directly from sensors and cameras while the other comes from available information systems that keep information generated and used in healthcare systems. Examples of these systems are electronic medical records (EMR)/electronic health records (EHR) systems that collect and keep patients' health information in a digital format including demographics, medications and allergies, medical history, immunization status, radiology images, laboratory test results, and other personal information; and healthcare human resources systems that maintain information about healthcare human resources such as their expertise, skills, schedules, and performance; and healthcare supply chain management systems that maintain information about all healthcare logistic and inventory needs. The information can also come from systems keeping healthcare equipment logs, healthcare facilities and equipment sensors data, IoT devices, and cameras.

The created digital twins are stored in a knowledgebase system as shown in the figure. This knowledgebase system contains the current virtual and digitalized model for a complete physical healthcare system. This knowledgebase system can be used by advanced healthcare system optimization and analytics tools to generate some healthcare improvement decisions to help achieve the main objectives of healthcare systems engineering. They can help in making management decisions through finding weaknesses, evaluating changes, and proposing alterations in the system to achieve the objectives. These objectives can be minimizing healthcare costs, improving healthcare services quality or accessibility, or improving other competitive advantage aspects. These decisions can generate recommendations for some adjustments or changes to some aspects of the healthcare systems. These may be changes to the current healthcare processes, adding more resources, reallocating resources, adding more healthcare partners, etc. These could also recommend modifying the current healthcare information systems to match and perfectly support the altered healthcare processes.

While most digital twins for healthcare systems engineering can be created and updated automatically in real-time, some manual involvement is needed for defining some physical aspects of healthcare systems. These include defining the healthcare organization where digital twins for healthcare systems engineering will be used as a system (or as a system of systems) and identifying the healthcare processes used in that system.

One possible approach to use for describing healthcare systems and processes is the use of a general-purpose system modeling language such as SysML [31]. SysML was designed to assist systems engineering activities such as systems analysis, design, evaluation, verification (to ensure that the systems are created to meet specified requirements), and validation (to ensure that the systems have met the true needs and expectations). SysML can model a system that has physical components, software components, processes, human resources, information, and facilities. In addition, SysML can be used for performance measurements, which are required by different evaluation and decision tools. Cost analysis can also be included by adding an extension to SysML [32]. Cost-related entities such as system and process operations costs and maintenance costs can be added to the modeling process and can be automatically computed. This allows healthcare systems engineers to easily perform different cost/benefit analyses for potential changes before applying them to the healthcare systems, a subsystem, or a specific process. Furthermore, other advanced analyses such as risk analysis [33]

TABLE 1. Example of digital twins for healthcare systems engineering.

#	Digital Twin Type	Digital Twin Examples	Digital Twin Content	Data Sources
1	Healthcare Human Resources (HR)	Doctors	Working hours and locations, main specialty, other specialties, schedules, average times spent for each medical consultancy and treatment type, salary, overtime salary, benefits, etc.	Healthcare HR systems Patients' medical records Personal tracking devices
		Nurses	Working hours and locations, main specialty, other specialties, skills, schedules, average times spent for each consultancy and treatment type, average time spent for different in-patient care tasks, salary, overtime salary, benefits, etc.	Healthcare HR systems Patients' medical records Personal tracking devices
		Lab technicians	Working hours and locations, main specialty, other specialties, skills, schedules, average time spent for each test type, salary, overtime salary, benefits, etc.	Healthcare HR systems Lab management systems Personal tracking devices
		Administrative and clerical staff	Working hours and locations, main specialty, other specialties, skills, average time completing patient-specific tasks like check in and check out, average time working on non-patient related asks, time spent assisting other workers (like doctors and managers), salary, overtime salary, benefits, etc.	Healthcare HR systems Work logs Personal tracking devices
2	Healthcare facilities and equipment	Treatment rooms	Average time in use, average number of patients treated, content inventory and costs, repairs and maintenance information and costs, number of times rooms are unavailable and the reasons, supplies and materials inventory and costs, housekeeping schedules and costs, etc.	Inventory systems and supply records Facilities maintenance systems Doctors/nurses records Housekeeping records IoT, CPS, sensors systems
		Surgical rooms	Average time in use, average number of patients treated, content inventory and costs, repairs and maintenance information and costs, number of times rooms are unavailable and the reasons, supplies and materials inventory and costs, housekeeping schedules and costs, etc.	Inventory systems and supply records Facilities maintenance systems Surgeons/Doctors and nurses' records Housekeeping records
		Intensive care units (ICU)	Average time in use, average number of patients treated, number of beds, average utilization of beds, average length of patient stays in ICU, content inventory and costs, repairs and maintenance information and costs, number of times rooms are unavailable and the reasons, supplies and materials inventory and costs, housekeeping schedules and costs, etc.	Inventory systems and supply records Facilities maintenance systems Doctors and nurses' records Housekeeping records IoT, CPS, sensors systems
		Emergency room	Average number of patients treated, number of beds, average utilization of beds, content inventory and costs, repairs and maintenance information and costs, number of times room (or part of it) is unavailable and the reasons, supplies and materials inventory and costs, housekeeping schedules and costs, etc.	Inventory systems and supply records Facilities maintenance systems Patients records. Doctors, nurses and staff records Housekeeping records IoT, CPS, sensors systems
		Consultancy rooms	Average time in use, average number of patients seen, number of doctors using a room, average length of patients' visits, content inventory and costs, repairs and maintenance information and costs, number of times rooms are unavailable and the reasons, supplies and materials inventory and costs, housekeeping schedules and costs, etc.	Inventory systems and supply records Facilities maintenance systems Doctors and nurses' records Housekeeping records IoT, CPS, sensors systems
		Pharmacy	Working hours, number of patients served, average length of time for the service, number of pharmacists, medications inventory and costs, content inventory and costs, repairs and maintenance information and costs, number of times unavailable and the reasons, supplies and materials inventory and costs, housekeeping schedules and costs, etc.	Inventory systems and supply records Medications supply records Facilities maintenance systems Pharmacists' records Housekeeping records IoT, CPS, sensors systems
		Laboratories	Working hours, types of tests, number of tests done of each type, average time for different types of tests, equipment inventory and costs, number of lab workers, records of repairs and changes to the lab and/or its content, number of times a lab (or equipment in it) is unavailable and the reasons, supplies and materials inventory and costs, housekeeping information and costs, etc.	Inventory systems and supply records Testing supplies records Facilities maintenance systems Lab technicians' records Housekeeping records IoT, CPS, sensors systems
		Waiting rooms	Working hours, capacity, average utilization, number of times capacity is reached/exceeded, content inventory and costs, repairs and maintenance information and costs, number of times unavailable and the reasons, supplies and materials inventory and costs, housekeeping schedules and costs, etc.	Inventory systems and supply records Facilities maintenance systems Clerical staff records Housekeeping records IoT, CPS, sensors systems
		Imaging rooms	Working hours, types of imaging services, number of imaging procedures done, average time for different types of procedures, equipment inventory and costs, number of workers, records of repairs and changes to the lab and/or its content, number of times a lab (or equipment in it) is unavailable and the reasons, supplies and materials inventory and costs, housekeeping information and costs, etc.	Inventory systems and supply records Imaging supplies records Facilities maintenance systems Radiologists' records Housekeeping records IoT, CPS, sensors systems

TABLE 1. *(Continued.)* Example of digital twins for healthcare systems engineering.

3	Healthcare supplies	Large equipment	Equipment uses, users, inventory, initial cost, condition, maintenance and repair information, warranties and licensing information, down times and their reasons, depreciation values, life expectancy, and average utilization, suppliers and repairs entities information, etc.	Equipment/supplies specifications Equipment/supplies operational procedures Inventory systems and supply records Suppliers' information Orders processing records Delivery and service records Accounting records Usage policies/processes IoT, CPS, sensors systems
		Reusable supplies	Supplies uses, users, inventory, initial cost, condition, usage costs (e.g., cost of cleaning), life expectancy, and average utilization and replacement, suppliers' information, etc.	
		Disposable supplies	Supplies uses, users, inventory, types, running cost, frequency of purchases, stored quantities, suppliers' information, etc.	
		Perishables	Uses, users, inventory, types, running cost, frequency of purchases, suppliers' information, etc.	
4	Healthcare processes	Procedures for units' use	Information on availability, utilization, personnel schedules, priority information, usage protocols, operational costs, etc.	Practically all healthcare processes will gather data from all available sources listed in this table. Additional sources of information are the partners and suppliers' information systems
		Appointments scheduling	Patients' information, personnel schedules, working hours, appointment type and needs, etc.	
		Doctors/Nurses scheduling	Specialty information, number of hours to work, past schedules, availability of backups, special requests, vacations and holidays information, patients and services frequencies and statistics, etc.	
		Patient admission and release processes	Patients' information, personnel schedules, availability information of rooms and other facilities needed, type and length of stay, special requirements, etc.	
		Maintenance scheduling	All information about buildings, rooms, services and equipment, facility's utilization patterns, personnel schedules, number of patients in the facility, estimated low/high service times, etc.	
		Housekeeping scheduling	Personnel schedules, rooms/areas usage patterns, in-patient admission rates, in-patient release patterns, number of patients in the facility, estimated low/high service times, etc.	
5	Healthcare partners	Insurance providers	Patients records, insurance plans details, insurance company's information, reporting mechanisms, etc.	Partners and suppliers' information systems
		External pharmacies	Patients records, pharmacy details, order and billing policies, medications requests mechanisms, etc.	
		Emergency response units	Facilities, capacity and usage information, personnel schedules, emergency room status, communication methods/channels, emergency/incident information.	
		Affiliated external service units	Patients records, external facility's details, service requests and information exchange mechanisms, etc.	
		Suppliers and service providers	Facility's operational records, inventory records, suppliers' information, types of supplies and frequency of orders, ordering and payment mechanisms, etc.	
6	Patients	In-patients	Patients records, current health status, healthcare needs, self-reported information on behavioral and psychological status, social and environmental information, etc.	Patients records. Personal tracking and health monitoring devices Self-reported information Facility and personnel information
		Out-patients	Patients records, current health status, healthcare needs, self-reported information on behavioral and psychological status, monitoring data, daily medications and dietary information and visitation records, etc.	

and safety analysis [34], [35] can be performed with SysML by adding other extensions. These analyses are also needed for healthcare systems engineering.

The optimization and evaluation tools can be built to use the targeted model of healthcare systems and the created digital twins for conducting different evaluations and proposing different actions to improve the healthcare systems. One possible option for better integration and utilization is generating digital models using SysML as well. This will allow the digital twins to be updated to reflect the actual status and performance of their corresponding physical healthcare components.

V. DIGITAL TWIN OPPORTUNITIES FOR HEALTHCARE SYSTEMS ENGINEERING

Using collected and compiled digital elements comprising the digital twins, it is possible to conduct different simulations about the present and future state of the components of healthcare systems. In such cases, the simulation parameters are configured on real data rather than random variables and estimations. As a result, the simulation outcomes are more realistic and can be confidently used for planning and decision making. This enables different capabilities including:

1. Reasoning about potential conditions for the present healthcare facilities, processes, human resources, patients, supplies, and partners before they take place. Running simulations representing current conditions will offer a good view of the status of operations and problem areas. This can also help monitor and control schedules and supplies inventories for example.
2. Predicting and possibly preventing unwanted or undesirable healthcare situations. The simulations can be extended by projecting future estimates to help predict changes and needs. For example, based on current consumption of supplies, it will be possible to identify an

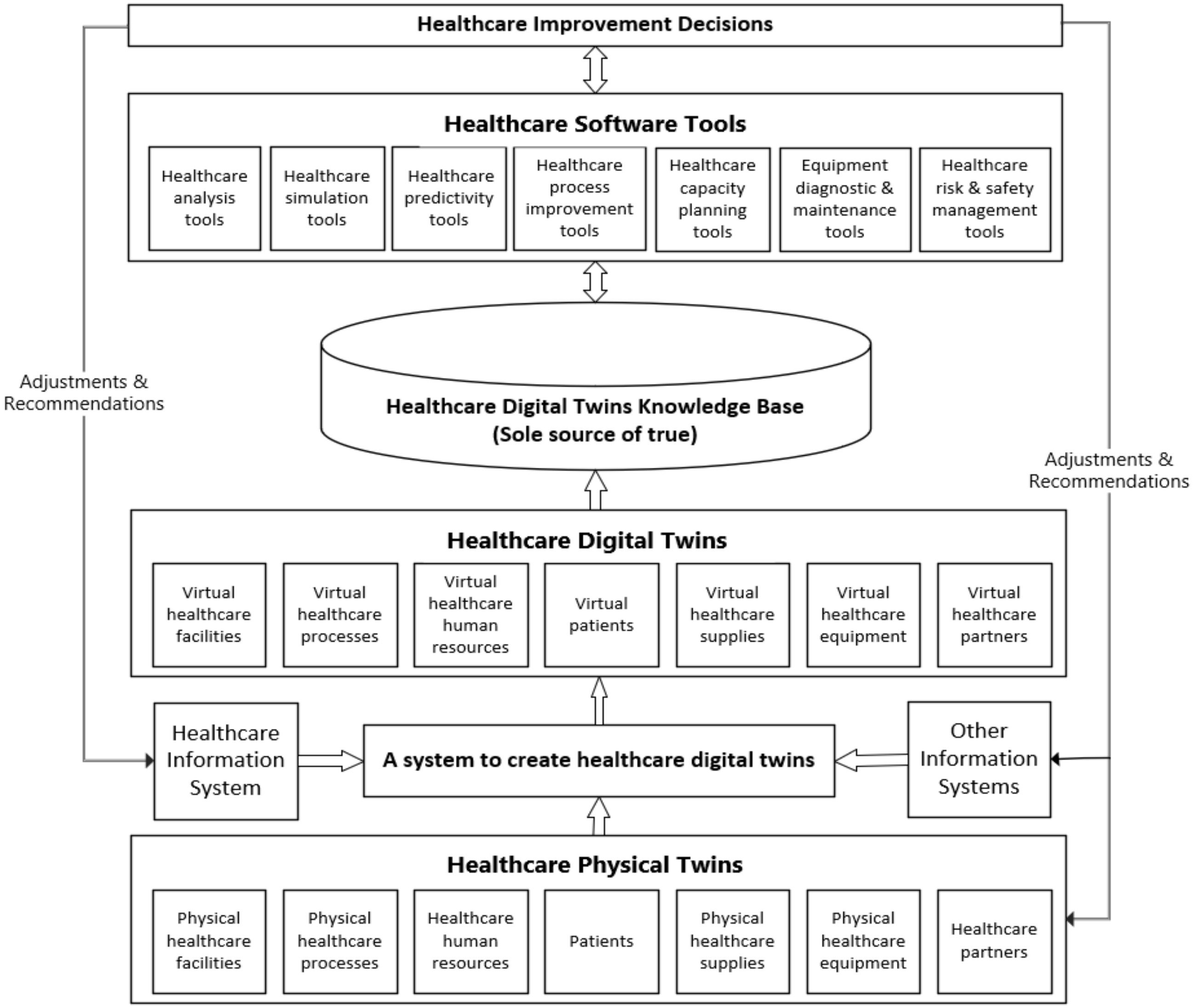


FIGURE 2. A conceptual framework for utilizing digital twins for healthcare systems engineering.

increase in using some supplies and initiate new orders in time.

3. Conducting operation optimizations for the different components of healthcare systems including healthcare facilities, processes, human resources, supplies, and partners. A simulation using the digital twin of a certain healthcare process, for example, will allow for imposing various changes on the process to see how it will work. As a result, it is possible to test optimization methods on the digital twin before applying them in the real system.
4. Understanding how a physical healthcare system or process is performing, and how it can be expected to perform in the future. A digital twin can be manipulated in various ways to focus on specific parts of the system, slow down or speed up operations, and magnify specific components to study them. This can help understand the detailed operations and all the factors affecting them.
5. Simulating different possible courses of action to determine suitability and applicability. With accurate inputs for the simulations, it is possible to deploy new or modified operations, introduce different scheduling models, or make changes in the supply chain and see the effects of such changes. This will help study various possible decisions and select the suitable ones.
6. Determining the best maintenance schedules for healthcare facilities and equipment. With complete and real-time records of facilities, equipment and supplies, it becomes easier to monitor the performance of equipment and health of the facilities. In addition, the information can also show the times when the systems are least used/needed. This information will help create better maintenance schedules to prevent failures, while minimizing disruptions.

The main functions of healthcare systems engineers are to deal with the components mentioned in the previous section to achieve the objectives listed in Section II, part B. Using advanced simulation approaches that use models created from digital twins for healthcare component types, it is possible to answer many decision questions about a healthcare system. Table 2 provides examples of these decision questions by specific healthcare systems engineering roles.

One of the most important advantages is that digital twins for healthcare systems engineering can be integrated with digitalized healthcare infrastructures such as Healthcare 4.0. Utilizing such integration, the engineers can more effectively deal with very dynamic health situations that could be caused by some pandemics such as COVID-19 [29]. In these situations, it is possible to utilize advanced simulations, optimization, and evaluations equipped with digital twins to find the best ways to use the limited available healthcare resources to provide support demanding healthcare services. Digital twins for healthcare systems engineering can form a complete virtual model of healthcare providers and their operations. This virtual model can be employed within Healthcare 4.0 to explore possible improvements in structure, resources, and flow mechanisms to lower redundant steps, speed up others or switch some with new improved ones in the virtual image [30]. This will assist in detecting problems, identifying the advantages of different possible modifications, and evaluating different healthcare scenarios before investing and deploying them.

VI. DIGITAL TWIN CHALLENGES FOR HEALTHCARE SYSTEMS ENGINEERING

1. **Data Collection**: This challenge is concerned with how data gathering about different healthcare processes, equipment, systems, facilities, healthcare human resources, healthcare partners, and other healthcare components can be performed effectively and efficiently. This collected data must be filtered, transferred, transformed, saved, and processed. This data can be from one healthcare branch or multiple healthcare branches. It can be internal data such as for internal healthcare processes, healthcare human resources, equipment, and facilities or external data from other organizations that provide medical supplies and equipment.
2. **Noise**: It is known that data collected from various sources will not be as clean as expected and will always carry noise. In addition, what is considered noise for some applications may be essential for others. One of the important challenges is identifying and removing the noise from collected data without losing actual useful data for the applications.
3. **Data Validation**: Another challenge is how the collected data can be validated. The gathered data can have noise, incomplete, heterogenous modalities (structured text, unstructured text, audio, image, video), and large size. The data cannot be well used unless it is validated to ensure that it represents the actual functions and characteristics of the physical healthcare components.
4. **Knowledge Extraction**: This challenge is about how knowledge extraction can be efficiently achieved. Starting with the validated data, knowledge composition methods are needed to create the specific knowledge needed in the various healthcare applications. Knowledge extraction is an important part of building accurate digital twins for the different aspects of healthcare systems engineering.
5. **Model Validation**: This challenge is about how to validate the created digital models to make sure that they represent their respective physical systems well. It is necessary that the created digital models are validated to make sure they provide accurate modeling and behaviors reflecting the physical elements before they can be used for different applications.
6. **Abstraction**: Digital models can be created with different levels of abstraction. They can be created with extensive details to include all aspects of the real worlds' physical components, systems, or processes or they can be created with a lot less details covering the information and operation behaviors needed for the current application and abstracting the rest of the details. Creating detailed digital models can reflect better the images of real worlds' physical components, systems, or processes. These detailed digital models can be used for current applications as well as future applications as the needs arise, and requirements change. However, these detailed models are more difficult to create and maintain than high-level abstracted models. Such comprehensive models require very lengthy, complicated, and costly processes. Abstractions are then important to reduce the complexity, while having enough coverage for high fidelity models. Therefore, it is important to select the right abstraction level in creating digital models to meet not only the current needs but also future application needs. Making this decision can be challenging as future needs are usually hard to predict.
7. **Automation**: another challenge and possibly the biggest one is how automating all the processes of data collection and validation, knowledge extraction, digital twins' development, and digital twins' validation can be effectively achieved. Although manual processes can be used, the created digital twins may not be accurate, flexible, nor real-time. Automation processes are needed to avoid human involvement and human mistakes and achieve real-time dynamic models. This automation can provide faster, and more accurate digital twins that can be utilized to get faster outcomes.
8. **Return on Investment Evaluation:** Another challenge, possibly one of the biggest, is non-technical and is concerned with how to measure the financial benefits and the costs of deploying digital twins to reduce the total costs of healthcare services in healthcare organization. This is usually needed to determine the feasibility of investing in such technology and

TABLE 2. Examples of decision questions that can be answered by using digital twins.

#	Healthcare SE Functions	Examples of decision questions
1	Creating vision, values, foundations, methods, tools, and practices to improve healthcare processes and systems.	- What is the impact of establishing a collaboration with a new healthcare partner? - What are the expected future healthcare loads? - What is the impact of utilizing new technology on healthcare processes?
2	Improving access to healthcare services for different types of patients.	- Will introducing new technology improve access to healthcare services? - What is the best location to open a new branch to improve overall access to healthcare services? - What is the impact of adding/removing a specific healthcare service at a specific healthcare branch?
3	Reducing healthcare services costs.	- Will costs be reduced by using new or modified healthcare processes? - What is the cost impact of using new healthcare technology? - What is the cost impact of introducing new work schedules for the human resources?
4	Examining various healthcare processes and systems to recommend constant improvements.	- What are the expected impacts of changing a healthcare process? - Which process among multiple suggested processes for the same healthcare task will provide the best outcomes? - Will a new process for a certain task lead to better results/performance?
5	Investigating various healthcare associated workloads and workforce engagements to propose enhanced healthcare operations and consequences.	- What is the impact of changing some healthcare task workloads on healthcare operations? - Does a specific workload change positively/negatively impact healthcare outcomes? - Will adding/removing/relocating resources improve workloads?
6	Enhancing the operations, utilization, usability, maintainability, and life of different medical equipment.	- What are the best schedules to conduct maintenance for medical equipment? - What is the best procedure to use to improve the utilization of medical equipment? - What is the impact of acquiring new medical equipment and/or retiring old ones?
7	Improving the utilizations and effectiveness of healthcare facilities such as treatment and operating rooms.	- What is the best procedure to improve the utilization of operating rooms? - What is the impact of adding or removing an operating room? - How to manage the supplies needed by different treatment and operating rooms?
8	Enhancing the reliability, effectiveness, management, and outcomes of different healthcare supply-chain processes and systems.	- What is the impact of using a new logistics process on the available supplies? - What are the future projections for supplies needs? - How will the availability of supplies change if we add more storage space?
9	Working on decreasing inconvenience and difficulties on healthcare professionals by enhanced planning, effective management, and optimized resources utilization.	- What is the impact of using new technology in reducing inconvenience and difficulties on healthcare professionals? - What is the impact of using new healthcare processes in reducing inconvenience and difficulties on healthcare professionals? - Will the introduction of assistive machines like robots reduce the complexity/difficulty of healthcare professionals' work?
10	Enhancing the safety of different healthcare facilities, processes, and systems.	- What is the expected safety level of using a new healthcare process? - What are the best tradeoffs between safety and costs for a specific healthcare system? - What is the best response process for safety incidents?
11	Working on detecting potential risks on healthcare processes and systems.	- What are the potential risks of using a new healthcare process or equipment? - Does a specific change in a healthcare process decrease potential risks? - What are the possible risks of introducing new technology?
12	Performing different capacity planning for the future healthcare services' expansions needs.	- What are the most needs for the coming specific period? - What is the impact of a specific future load on the current healthcare resources? - How to prioritize fulfilling upcoming needs for best results?

ensure that the total benefits will exceed the total cost of the investment. Thus, leading to a good return on investment (ROI) for developing and deploying digital twins for healthcare service providers. Different healthcare service providers may achieve different levels of financial benefits from this investment. A large healthcare service provider that has several opportunities for cost savings will achieve more financial benefits if they deploy digital twins compared to a small provider. Furthermore, the costs of deploying and using digital twins for different healthcare service providers vary. The total cost can be relatively small for a healthcare service provider already invested in technology solutions and has a good level of digitalization in their systems for equipment, facilities, processes, and buildings.

VII. DISCUSSIONS AND FUTURE PROSPECTS

This section discusses the impact of digital twin technology on healthcare systems engineering and offers some prospects. This impact is shown in Figure 3. The first lower layer in this figure shows the digital twins enabling technologies. This layer includes sensors, Internet of Things (IoT), Cyber-Physical Systems (CPS), and cloud and edge computing technologies. In addition, it includes the driving engines to produce the desired effects of the collected data. These include data analytics methods, data and process mining, artificial intelligence algorithms, and machine learning tools. All these technologies enable the creation of digital twins in healthcare representing the different components of the systems and services. These digital twins are shown in the second layer on top of the enabling technologies. These digital twins represent the different components of the

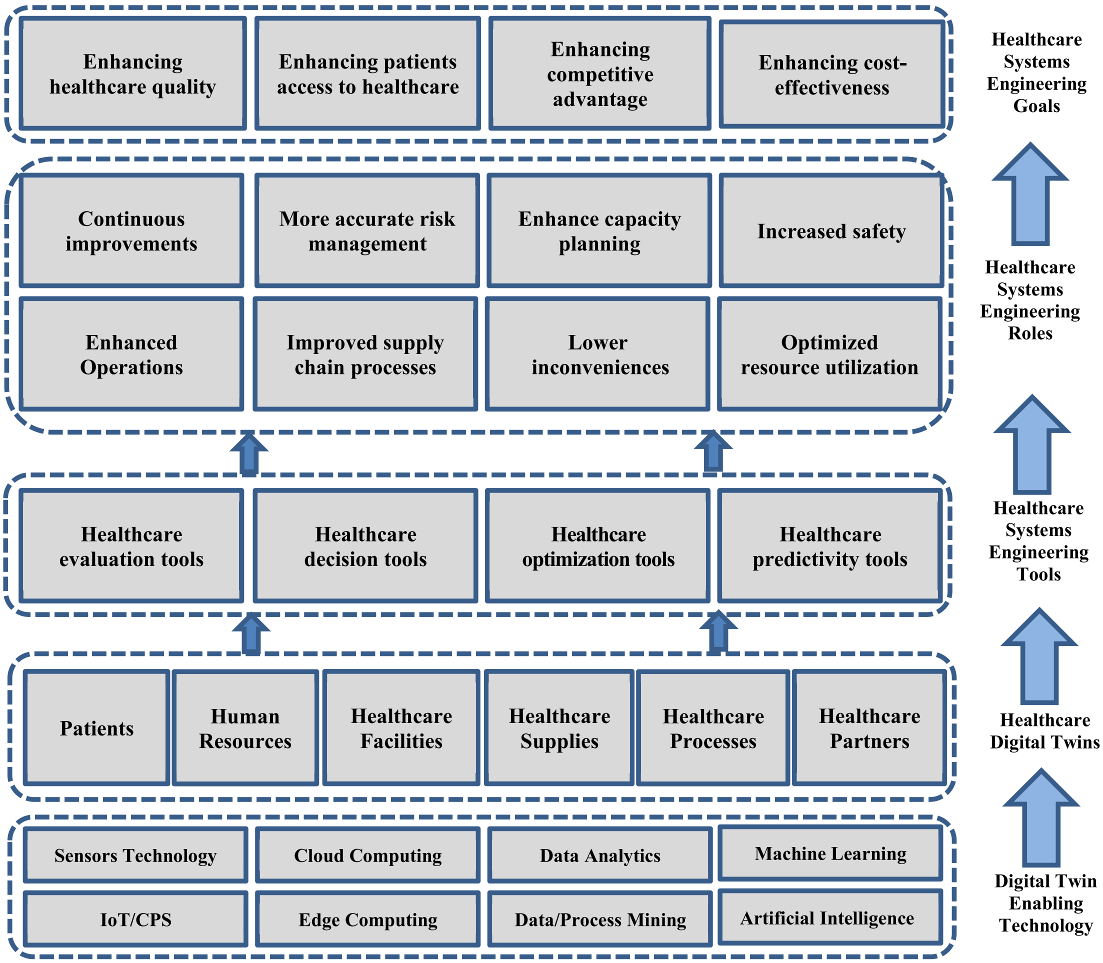


FIGURE 3. An impact architecture of digital twin on healthcare systems engineering.

healthcare systems such as the patients, resources, facilities, and partners. They can be integrated with tools that can help significantly improve the healthcare systems' operations and outcomes. These include tools like simulations, evaluation mechanisms, decision making capabilities, optimization techniques, and predictive analytics methods. These tools can used by healthcare systems engineers to achieve the systems engineering functions such as continuous healthcare services improvements, enhanced healthcare operations, more accurate healthcare risk management, improved healthcare supply chain processes, enhanced capacity planning, lower inconveniences, increased healthcare safety, and optimized resource utilization. All these roles help in achieving the main goals of healthcare systems engineering in enhancing healthcare services quality, patients access to healthcare services, competitive advantage, and cost-effectiveness.

As we discussed in the previous sections, digital twins can provide many opportunities for developing the processes and outcome of healthcare systems engineering; however, more research and development are needed to address the challenges and increase the practicality and feasibility of using digital twins. Here, we discuss some possible avenues for future research and development regarding the utilization of digital twins for healthcare systems engineering. Employing digital twins can provide a realistic representation and an infrastructure to enable solutions for the challenges of healthcare systems engineering such as those discussed in Section III. In addition, digital twins can be used to assist in creating autonomous and fully automated solutions that can further help address some of these challenges.

The challenge of identifying current and persistent healthcare issues in the healthcare organization can be solved by developing advanced inspection software tools capable of inspecting the actual models of the healthcare organization and their digital twins to identify issues. These tools can compare the performance of the healthcare systems and its components with available benchmarks (pre-defined or collected earlier) to identify such issues. The challenge of understanding the details of the existing healthcare issues and their root causes can be solved by having additional software tools that can trace the related digital twins to try to find the root causes of each issue. Qafari and van del Aalst [36] developed a root cause analysis technique based on process mining and structural equation models. This technique can be utilized with digital twins to find root causes for healthcare issues by digging through time stamped snapshots of the digital twins over time. This helps healthcare organizations to focus on solving the root causes of the issues and improve their performance indicators.

The challenge of identifying different possible alternative solutions for each healthcare issue can be simplified as the virtual model for the whole healthcare organization or service provider will be available and it is easy to find different possible solutions by analyzing that digital model without dealing with any physical aspects. In this regard, it is possible to make subtle changes in one or more components of the virtual model to see if the changes can provide some improvements compared to the original model (sort of like debugging code). The challenge of evaluating alternative solutions to select the best solution to solve some healthcare issue can also be relaxed as all these evaluations can be conducted using simulations for the different solutions on the virtual models rather than tampering with the actual model or trying to estimate the outcomes. The simulations here become detailed and accurate as they rely on real live streams of systems performance to compare different solutions and their outcomes. In the same manner, after selecting the best solution, developing, evaluating, and selecting the best implementation among multiple implementation possibilities for the solution can be easily achieved using similar simulations. Furthermore, deploying any solution can be evaluated and compared with the original model under different conditions including some future anticipated conditions to comprehensively assess the impact of the applied solution on the healthcare organization.

The above discussed points can provide a roadmap for the future research and development efforts for improving the utilization of digital twins for healthcare systems engineering and maximizing the benefits of such utilization.

VIII. CONCLUSION

This work explored how healthcare systems engineering can benefit from utilizing the digital twin technologies. A conceptual framework for utilizing digital twins for healthcare systems engineering was discussed. This framework can assist in improving the processes and outcomes of healthcare systems engineering. In this framework, digital twins representing different components of the healthcare systems were discussed. These digital twins are for patients, healthcare human resources, healthcare facilities and equipment, healthcare supplies, healthcare processes, and healthcare partners. These digital twins can then be augmented with advanced analysis, data analytics, decision making, and monitoring tools to assist the decision-making processes. Tools like simulations, predictive analytics, process improvements, capacity planning, diagnostics and maintenance management, and risk and safety management will allow healthcare decision makers to know about hidden and possible healthcare issues and about potential improvements and to effectively make the right decisions and apply the right actions to fix the issues and/or optimize the processes in a timely manner.

As a result, better decisions can be made to significantly improve the healthcare systems engineering processes and outcomes to achieve the main goals of healthcare organizations in improving healthcare quality, facilitating better patients access to healthcare services, and improving their competitive advantage. In addition, utilizing digital twins for healthcare systems engineering can enable rapid responses to react for very dynamic health situations that could be caused by natural disasters or pandemics like COVID-19.

REFERENCES

[1] N. Mohamed and J. Al-Jaroodi, "The impact of industry 4.0 on healthcare system engineering," in *Proc. IEEE Int. Syst. Conf. (SysCon)*, Orlando, FL, USA, Apr. 2019, pp. 1–7.

[2] T. Erol, A. F. Mendi, and D. Dogan, "The digital twin revolution in healthcare," in *Proc. 4th Int. Symp. Multidisciplinary Stud. Innov. Technol. (ISMSIT)*, Oct. 2020, pp. 1–7.

[3] H. Hassani, X. Huang, and S. MacFeely, "Impactful digital twin in the healthcare revolution," *Big Data Cogn. Comput.*, vol. 6, no. 3, p. 83, 2022.

[4] S. Khan, T. Arslan, and T. Ratnarajah, "Digital twin perspective of fourth industrial and healthcare revolution," *IEEE Access*, vol. 10, pp. 25732–25754, 2022.

[5] T. Sun, X. He, and Z. Li, "Digital twin in healthcare: Recent updates and challenges," *Digital Health*, vol. 9, pp. 1–12, Jan. 2023.

[6] H. Garg, "Digital twin technology: Revolutionary to improve personalized healthcare," *Sci. Prog. Res.*, vol. 1, no. 1, pp. 31–34, Dec. 2020.

[7] R. Sahal, S. H. Alsamhi, and K. N. Brown, "Personal digital twin: A close look into the present and a step towards the future of personalised healthcare industry," *Sensors*, vol. 22, no. 15, p. 5918, Aug. 2022.

[8] S. D. Okegbile, J. Cai, C. Yi, and D. Niyato, "Human digital twin for personalized healthcare: Vision, architecture and future directions," *IEEE Netw.*, early access, Jul. 25, 2022, doi: 10.1109/MNET.118.2200071.

[9] O. C. Madubuike and C. J. Anumba, "Digital twin application in healthcare facilities management," *Comput. in Civil Eng.*, vol. 2021, pp. 366–373, Jan. 2021.

[10] C. Patrone, G. Galli, and R. Revetria, "A state of the art of digital twin and simulation supported by data mining in the healthcare sector," in *Advancing Technology Industrialization Through Intelligent Software Methodologies, Tools and Techniques*. Amsterdam, The Netherlands: IOS Press, 2019, pp. 605–615.

[11] J. Zhang, L. Li, G. Lin, D. Fang, Y. Tai, and J. Huang, "Cyber resilience in healthcare digital twin on lung cancer," *IEEE Access*, vol. 8, pp. 201900–201913, 2020.

[12] R. Rardin, "Research agenda for healthcare systems engineering," Nat. Sci. Found., Alexandria, VI, USA, Tech. Rep., 2007.

[13] P. M. Griffin, H. B. Nembhard, C. J. De Flitch, N. D. Bastian, H. Kang, and D. A. Muñoz, *Healthcare Systems Engineering*. Hoboken, NJ, USA: Wiley, 2016.

[14] M. Grieves, "Virtually intelligent product systems: Digital and physical twins," in *Complex Systems Engineering: Theory and Practice*, S. Flumerfelt, Ed. Reston, VA, USA: American Institute of Aeronautics and Astronautics, 2019, pp. 175–200.

[15] A. Croatti, M. Gabellini, S. Montagna, and A. Ricci, "On the integration of agents and digital twins in healthcare," *J. Med. Syst.*, vol. 44, no. 9, pp. 1–8, Sep. 2020.

[16] G. Ahmadi-Assalemi, H. Al-Khateeb, C. Maple, G. Epiphaniou, Z. A. Alhaboby, S. Alkaabi, and D. Alhaboby, "Digital twins for precision healthcare," in *Cyber Defence in the Age of AI, Smart Societies and Augmented Humanity*. Cham, Switzerland: Springer, 2020, pp. 133–158.

[17] C. Angulo, L. Gonzalez-Abril, C. Raya, and J. A. Ortega, "A proposal to evolving towards digital twins in healthcare," in *Proc. Int. Work-Conf. Bioinf. Biomed. Eng.* Cham, Switzerland: Springer, 2020, pp. 418–426.

[18] L. F. Rivera, M. Jiménez, P. Angara, N. M. Villegas, G. Tamura, and H. A. Müller, "Towards continuous monitoring in personalized healthcare through digital twins," in *Proc. 29th Annu. Int. Conf. Comput. Sci. Softw. Eng.*, 2019, pp. 329–335.

[19] I. Volkov, G. Radchenko, and A. Tchernykh, "Digital twins, Internet of Things and mobile medicine: A review of current platforms to support smart healthcare," *Program. Comput. Softw.*, vol. 47, no. 8, pp. 578–590, Dec. 2021.

[20] D. Gupta, O. Kayode, S. Bhatt, M. Gupta, and A. S. Tosun, "Hierarchical federated learning based anomaly detection using digital twins for smart healthcare," in *Proc. IEEE 7th Int. Conf. Collaboration Internet Comput. (CIC)*, Dec. 2021, pp. 16–25.

[21] N. Wickramasinghe, P. P. Jayaraman, A. R. M. Forkan, N. Ulapane, R. Kaul, S. Vaughan, and J. Zelcer, "A vision for leveraging the concept of digital twins to support the provision of personalized cancer care," *IEEE Internet Comput.*, vol. 26, no. 5, pp. 17–24, Sep. 2022.

[22] A. Ricci, A. Croatti, and S. Montagna, "Pervasive and connected digital twins—A vision for digital health," *IEEE Internet Comput.*, vol. 26, no. 5, pp. 26–32, Sep. 2022.

[23] S. P. Ramu, P. Boopalan, Q.-V. Pham, P. K. R. Maddikunta, T. Huynh-The, M. Alazab, T. T. Nguyen, and T. R. Gadekallu, "Federated learning enabled digital twins for smart cities: Concepts, recent advances, and future directions," *Sustain. Cities Soc.*, vol. 79, Apr. 2022, Art. no. 103663.

[24] A. De Benedictis, N. Mazzocca, A. Somma, and C. Strigaro, "Digital twins in healthcare: An architectural proposal and its application in a social distancing case study," *IEEE J. Biomed. Health Informat.*, early access, Sep. 9, 2022, doi: 10.1109/JBHI.2022.3205506.

[25] M. N. Kamel Boulos and P. Zhang, "Digital twins: From personalised medicine to precision public health," *J. Personalized Med.*, vol. 11, no. 8, p. 745, Jul. 2021.

[26] J. Al-Jaroodi, N. Mohamed, and E. Abukhousa, "Health 4.0: On the way to realizing the healthcare of the future," *IEEE Access*, vol. 8, pp. 211189–211210, 2020.

[27] J. Al-Jaroodi, N. Mohamed, N. Kesserwan, and I. Jawhar, "Healthcare 4.0—Managing a holistic transformation," in *Proc. IEEE Int. Syst. Conf. (SysCon)*, Apr. 2022, pp. 1–8.

[28] M. Alazab, L. U. Khan, S. Koppu, S. P. Ramu, I. M. P. Boobalan, T. Baker, P. K. R. Maddikunta, T. R. Gadekallu, and A. Aljuhani, "Digital twins for healthcare 4.0—Recent advances, architecture, and open challenges," *IEEE Consum. Electron. Mag.*, early access, Sep. 23, 2022, doi: 10.1109/MCE.2022.3208986.

[29] J. Al-Jaroodi and N. Mohamed, "Healthcare 4.0 significance and benefits affirmed by the COVID-19 pandemic," in *Digital Innovation for Healthcare in COVID-19 Pandemic*, New York, NY, USA: Academic, 2022, pp. 307–330.

[30] N. Mohamed, J. Al-Jaroodi, and E. AbuKhousa, "Enabling healthcare 4.0 applications development through a middleware platform," in *Digital Innovation for Healthcare in COVID-19 Pandemic*. New York, NY, USA: Academic, 2022, pp. 263–305.

[31] S. Friedenthal, A. Moore, and R. Steiner, *A Practical Guide to SysML: The Systems Modeling Language*. Burlington, MA, USA: Morgan Kaufmann, 2014.

[32] C. Kotronis, M. Nikolaidou, A. Tsadimas, C. Michalakelis, and D. Anagnostopoulos, "Extending SysML to integrate cost analysis into model-based systems engineering," *IEEE Trans. Eng. Manag.*, early access, Aug. 31, 2022, doi: 10.1109/TEM.2022.3200148.

[33] F. Shirvani, W. Scott, G. A. L. Kennedy, and A. P. Campbell, "Enhancement of FMEA risk assessment with SysML," *Austral. J. Multi-Disciplinary Eng.*, vol. 15, no. 1, pp. 52–61, Jan. 2019.

[34] H. Wang, D. Zhong, T. Zhao, and F. Ren, "Integrating model checking with SysML in complex system safety analysis," *IEEE Access*, vol. 7, pp. 16561–16571, 2019.

[35] F. Mhenni, N. Nguyen, and J. Choley, "SafeSysE: A safety analysis integration in systems engineering approach," *IEEE Syst. J.*, vol. 12, no. 1, pp. 161–172, Mar. 2018.

[36] M. S. Qafari and W. van der Aalst, "Root cause analysis in process mining using structural equation models," in *Proc. Int. Conf. Bus. Process Manag.*, vol. 18. Cham, Switzerland: Springer, 2020, pp. 155–167.

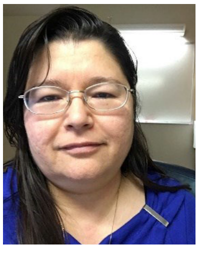
[37] Y. Feng, "Create the individualized digital twin for noninvasive precise pulmonary healthcare," *Significances Bioeng. Biosci.*, vol. 1, no. 2, pp. 1–10, Jan. 2018.

[38] B. Subramanian, J. Kim, M. Maray, and A. Paul, "Digital twin model: A real-time emotion recognition system for personalized healthcare," *IEEE Access*, vol. 10, pp. 81155–81165, 2022.

[39] Y. Liu, L. Zhang, Y. Yang, L. Zhou, L. Ren, F. Wang, R. Liu, Z. Pang, and M. J. Deen, "A novel cloud-based framework for the elderly healthcare services using digital twin," *IEEE Access*, vol. 7, pp. 49088–49101, 2019.

[40] H. Elayan, M. Aloqaily, and M. Guizani, "Digital twin for intelligent context-aware IoT healthcare systems," *IEEE Internet Things J.*, vol. 8, no. 23, pp. 16749–16757, Dec. 2021.

NADER MOHAMED (Member, IEEE) received the Ph.D. degree in computer science from the University of Nebraska-Lincoln, Lincoln, NE, USA, in 2004. He was a Faculty Member with the Stevens Institute of Technology, Hoboken, NJ, USA, and United Arab Emirates University, Al Ain, United Arab Emirates. He also has several years of industrial experience in information technology. He is currently an Associate Professor in computer science and information systems with Pennsylvania Western University, California, PA, USA. His current research interests include middleware, industry 4.0, digital twins, energy efficiency, smart systems, cloud and fog computing, networking, healthcare systems, cyber-physical systems, and cybersecurity.



JAMEELA AL-JAROODI (Member, IEEE) received the Ph.D. degree in computer science from the University of Nebraska–Lincoln, Nebraska, USA, and the M.Ed. degree in higher education management from the University of Pittsburgh, PA, USA. She was a Research Assistant Professor with the Stevens Institute of Technology, Hoboken, NJ, USA, and then an Assistant Professor with United Arab Emirates University, United Arab Emirates. Then, she was an independent researcher in computer and information technology. She is currently a Professor and a Coordinator of the software engineering concentration with the Department of Engineering, Robert Morris University, Pittsburgh, PA, USA. She is involved in various research areas, including middleware, software engineering, security, and distributed and cloud computing, in addition to UAVs and wireless sensor networks.

IMAD JAWHAR (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from the University of North Carolina at Charlotte, USA, the M.S. degree in computer science, and the Ph.D. degree in computer engineering from Florida Atlantic University, USA. He is currently a Professor and the Chairman of Computer Engineering with the Faculty of Engineering, Al Maaref University, Beirut Lebanon. He was a Faculty Member for several years with Florida Atlantic University. He has published numerous papers in international journals, conference proceedings, and book chapters. He was with Motorola as the Engineering Task Leader involved in the design and development of IBM PC-based software used to program the world's leading portable radios and cutting-edge communication products and systems, providing maximum flexibility and customization. He was also the President and the Owner of Atlantic Computer Training and Consulting, which is a company based on South Florida, USA, that trained 1000's of people and conducted numerous classes in the latest computer system applications. Its customers included small and large corporations, such as GE, Federal Express, and International Paper. His current research interests include cyber-physical systems, wireless networks and mobile computing, sensor networks, routing protocols, and distributed and multimedia systems. He served on numerous international conference committees and reviewed publications for many international journals, conferences, and other research organizations, such as the American National Science Foundation (NSF). He is a member of ACM and ACS organizations.

NADER KESSERWAN received the Ph.D. degree in information systems and engineering from Concordia University, Montreal, Canada. He is currently an Assistant Professor in the software engineering concentration with the Department of Engineering, Robert Morris University, Pittsburgh, PA, USA. His research interests include model-based testing, the IoT security, wireless sensor networks, and software engineering.