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FRAMEWORK FOR A HYBRID SIMULATION APPROACH FOR AN INTEGRATED DECISION SUPPORT SYSTEM IN HEALTHCARE FACILITIES

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ABSTRACT

There is a lack of integration of facility planning techniques in the design and layout of healthcare facilities. Computational models can be used to evaluate minimal distances or cost functions. Discrete event simulations can be used to model the stochastic nature of operations to check the impact on specific performance measures. Visualization can be used to immerse decision makers in the future environment to aid model validity, communication, and understanding. In this paper, we discuss three techniques: mathematical optimization, discrete event simulation, and virtual visualization, and present a framework for using them in an integrated hybrid simulation modeling approach in the healthcare planning process. We present objectives for the use of these techniques throughout the lifecycle in one unit of a healthcare facility. These techniques, while described in a healthcare context, have implications for other domains where uncertain and latent processes are components of the layout decision making process.

1 INTRODUCTION

Healthcare professionals are increasingly asking for evidence of the functional requirements of facility designs (Burmahl et al. 2017). Design has typically been based on expert knowledge from both design and healthcare practitioners. In order to enable data-driven approaches, this expertise needs to be formalized in the optimization-simulation process. Typical methods used by operations researchers are not frequently used in the design phase of healthcare facilities. A recent review of the use of simulation in healthcare facilities found research in design and capacity planning was limited (Arisha and Rashwan 2016). Similarly, scenario planning was identified as promising but a limited area of research for healthcare (Rais and Viana 2011). Part of the reason for the lack of simulation in planning and design is a lack of understanding from both architects and healthcare practitioners (Arnolds and Nickel 2015; Holst 2015).

Facility layout problems are an important class of problems for operations research. In the classic example of the optimization healthcare layout problem, Elshafei (1977) explains the problem of minimizing distance traveled by patients, formulated as a Quadratic Assignment Problem (QAP). While this is a classic problem for facility layout problems, in context for designing and constructing new and renovated healthcare facilities, this method doesn't connect the processes of a future facility to the implementation of the QAP. Location and layout optimization is typically done in early stages of the design process when little is known about the new processes to be implemented in the renovated/new facility yet needs data about appropriate flow weights or costs, depending on the formulation, to accurately find optimal layout arrangements. Some research (Acar et al. 2009; Arnolds and Nickel 2015) has looked at an optimization-simulation approach in these healthcare layout planning problems.

Increase in immersive visualization is one of the key features of communication between model creators and decision makers (O'Keefe 2016). Virtual reality allows healthcare professionals to experience their space. Discrete event simulation (DES) allows healthcare practitioners to test their workflow processes. Virtual reality has been used in the design evaluation process to allow those not familiar with 2D plans and sections to have a greater understanding of the spatial arrangement and spatial decisions they are making (Van Der Land et al. 2013). 3D visualization has been found to be beneficial in the evaluation of DES models (Akpan and Shanker 2017). Typical software (e.g., Simio, Flexsim) displays have incorporated advanced visualization features including 2D, 3D visualization, walkthrough and animation functionality. However, the features alone don't address including visualization criteria into the hybrid simulation methodology. The integration of an optimization-simulation-visualization (OSV) framework can allow for a more iterative structure combining the mathematical and simulation approaches with immersive visualization evaluation of new processes in future healthcare facilities to allow for a combined human-centered and data-driven approach.

2 CONTEXT FOR APPROACH

The context for facility planning should be placed in the facility lifecycle and the objective of the facility (for example, in this application area: patient care). In this section, we explore the context of both the facility lifecycle and an overview of the patient evaluation process.

2.1 Building Lifecycle Process

The building lifecycle is made up of 5 distinct processes: manage, plan, design, construct, and operate, (Sanvido et al. 1990). Manage includes the business side of building a facility. Plan defines what the owner of a facility needs, such as the idea of a new facility or a redesign and developing a program of specific functions and space requirements needed in that facility. Design consists of functions that communicate the owner's needs with the design team and transforms those into the design, bid documents, and construction plans. Construct comprises all the building activities from demolition to all assembly activities. Operate includes all the operational activities of the facility, including turnover, operations, and maintenance. From an overview of these processes, manage is the activity which lasts consistently through all stages of the building lifecycle and connects to all the other aspects of the design and operations lifecycle (Figure 1).

These processes are interconnected and can be modeled as distinct parts with inputs, mechanisms, controls, and outputs (Figure 2). When investigating the integrated process, it is common to think of the plan, design, construct, and operate activities as predecessors to one another. If we add redesign to the scope, we have a full circle process (Figure 1). However, these processes are interdependent in ways that are more complex than any linear or cyclical depiction. Sanvido et al. (1990) began to investigate the inputs and outputs of these processes. In the Integrated Building Process Model, outputs from design, construction, and operations of a facility feedback into the manage, plan, and design processes of a new or

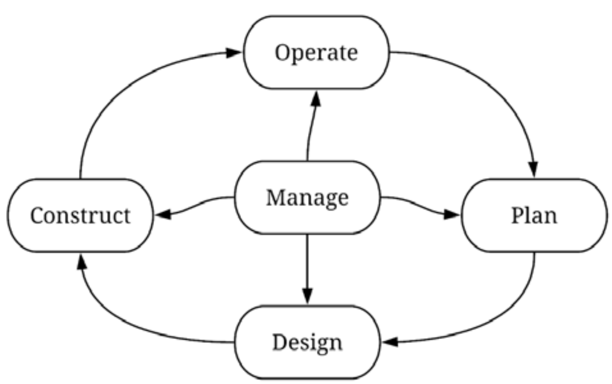

Figure 1: Overview of elements of providing a facility.

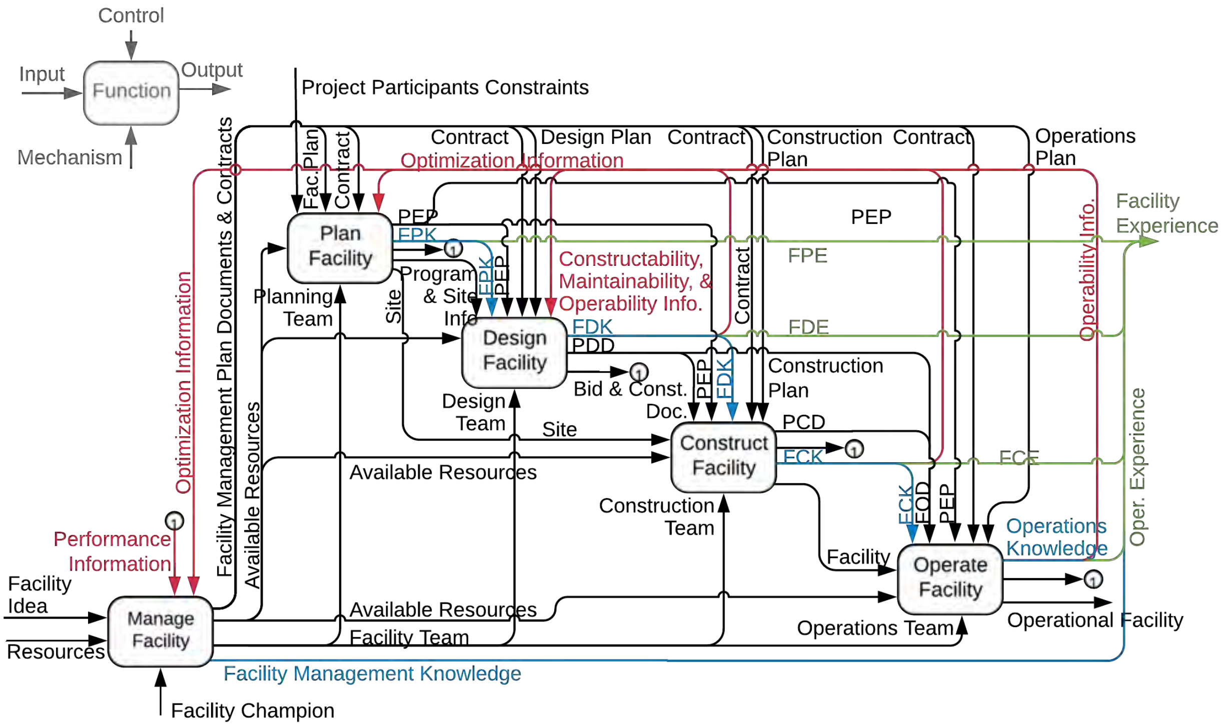

Figure 2: Elements of providing a facility in the Integrated Building Process Model. Red highlights feedback from Design, Construction, and Operations into Manage, Plan, and Design. Blue indicates knowledge output. Green indicates experience of the facility resulting from all phases (Sanvido et al. 1990).

renovated facility (Figure 2), typically as best practices (blue to red lines) and knowledge of what worked and what didn't which becomes how the project team and owners experience the facility (blue to green lines). Managers of facilities collect "performance information" for the facility overall and "optimization information" to evaluate project performance and facility performance. In the process model, optimization information means the information used to integrate the expertise of participants, including designability, constructability, operability, and maintainability information. This information constrains the manage activities. This same information is used control the plan and the design and, in turn, impacts how facility owners and users experience the facility. The question arises: how can we better include performance evaluation of the design and operations in the design and construction processes?

2.2 Integrated Simulation

An integrated technique is needed if we want to leverage the computational techniques effectively in the design of healthcare facilities. Gibson (2007) discussed using discrete event simulation for scenario testing in the schematic design stage of healthcare projects, yet is not commonly shown in the literature or implemented in practice. Visualization techniques can be used in future applications to improve the understanding among the disparate team members, expand the use cases of experiencing new processing before buildings are built, and implement continuous improvement cycles between design and operations. Integrating layout analysis, healthcare processes, and spatial visualization may provide a framework where each approach builds off one another while alleviating common implementation and communication problems.

2.3 Patient Flow Process

Patients flow is an important area of research for healthcare professionals. Healthcare simulation research has been a popular application area throughout the history of the Winter Simulation Conference as highlighted in a review of healthcare simulation (Arisha and Rashwan 2016). Managers are interested in performance measures such as length of stay of patients. Less research has been on the use of simulation in design and planning of healthcare applications, such as in layout or bed capacity analysis (Arisha and Rashwan 2016).

Patients go through a series of processes when they visit a healthcare facility. In the context of an emergency department, the main processes include registration, triage, evaluation, diagnosis, treatment, and discharge (Figure 3). A patient may need tests, medications, or procedures. A patient may be admitted to the main hospital or transferred to a different facility. These processes may happen in different locations of the emergency department. A patient who arrives by ambulance in critical care will immediately be brought to the room or bed needed for care. A patient who isn't critical typically only has the processes after triage conducted in a room/bed. A patient who doesn't need much care, such as an emergency severity index (ESI) 4 or 5 patient, might not take up space in a bed for longer than evaluation. Bed resource allocation is dependent on the processes that the healthcare unit deploys, but information on future processes is typically not known during the capacity planning or layout of a facility. The experience of the professionals involved in the functioning of the facility is used in the design process to evaluate the layout and provide guidance on optimal configuration. But if the processes are unknown, the decisions are not made with adequate information.

3 RELATED SIMULATION WORK

In this section, we will discuss an overview of simulation and optimization approaches in the literature and discuss how they are used for healthcare facility planning. A considerable amount of research has been done in this area, and below we will touch on a few of the key areas related to this approach.

3.1 Optimization and Facility Layout Design

Facility layout optimization problems are often NP-hard mathematical problems (Anjos and Vieira 2017). Many researchers have investigated methods to solve optimization problems for the layout of healthcare facilities. These layout solutions are usually a combination of minimizing distance and flow cost between operational units (weighted average by daily trips).

Anjos and Vieira (2017) discuss the current state of mathematical layout optimization in three classes of problems: row layout, multi-level, and unequal areas. Unequal areas is a commonly investigated class of facility layout problems, followed by row layout, which has seen recent advances, and lastly, multi-level

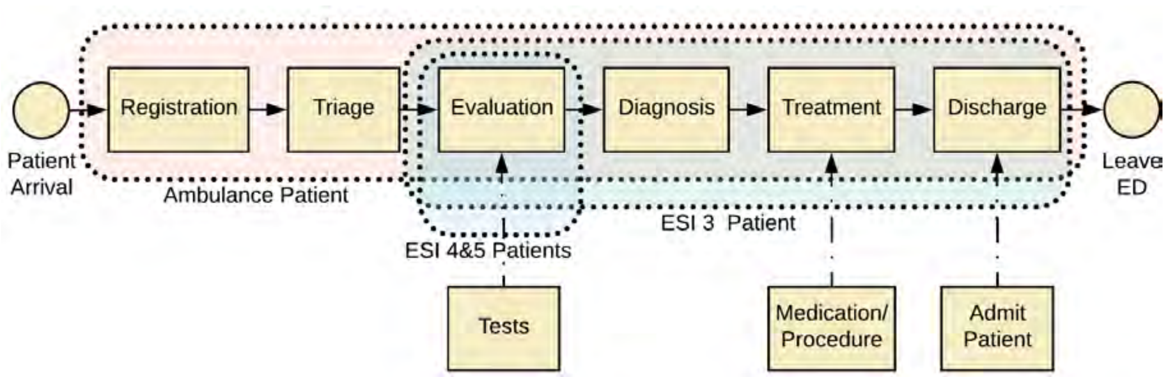

Figure 3: Typical emergency room patient processes. Containers indicate parts in the process where a patient is roomed. These change based on the condition of the patient and healthcare processes.

problems are the least common and most difficult computationally. For more work on the row layout (corridor allocation problem) see Amaral (2012). While the mathematical optimization techniques are useful for understanding how to obtain globally optimal solutions to layout problems, they do not take into account the facility operations. In application, a simulation-optimization approach might be more appropriate to find an optimal solution with uncertain processes. In a review of layout planning problems, Arnolds and Nickel (2015) presented literature from 55 articles on various methodologies including quadratic assignment problems, mixed integer programs, and discrete event simulations. They suggested a framework for integrating deterministic optimization techniques with stochastic simulation.

3.2 Healthcare Layout and Design Studies

Not only minimal distance or flow cost is important for healthcare layout optimization. Views to rooms, room assignments, and environmental factors can be important factors in the design of a facility layout. There has been a considerable amount of post-occupancy research investigating healthcare layout and design and how to it impacts important metrics associated with a department, namely nurse movement and efficiency of delivered care. In a study aimed at understanding the relationship between different spatial measures and nurse movement, Choudhary et al. (2010) found different organizational strategies for pods of beds being served by nurses led to significant changes in the number of trips to patients beds. While many factors contribute to the number of visits to patients beds including policy and layout, the study did also find that patients who were seen more frequently also had more time with the nurse. The findings show that spatial arrangement impacts time spent with patients when processes and procedures are similar.

3.3 Discrete Event Simulation in Healthcare

Discrete Event Simulation is a common technique in operations research to simulate healthcare processes in departments to understand how operational changes will impact specific performance measures. Implementation is one of the more difficult areas of DES research because decision-makers usually need solutions to problems urgently and thus timing, adequate data collection, and oversimplification can lead to a lack of confidence in the technique (GÜNal and Pidd 2010).

There have been several studies investigating both process changes and layout changes in clinical healthcare settings. Farahmand et al. (2011) investigated changes to the staff allocation assignments in a healthcare clinic in concert with minimizing distances. While layout wasn't the main aspect of their study, they modeled patient movement as a stochastic time variable in their discrete event simulation. This method allows some patients to walk faster than others which might be more realistic when distances are known.

3.4 Virtual Reality in Discrete Event Simulation

Researchers have described the integration of simulation and visualization as helpful for early design decisions (Waller and Ladbrook 2002), increased model understanding (Akpan and Brooks 2014), improved model error identification (Akpan and Brooks 2014), demonstrating the model to the client (Akpan and Brooks 2012), and improved decision making (Chau and Bell 1995). The use of virtual reality in the validation of discrete event simulations has been the most common area cited for the integration of these techniques (Rekapalli and Martinez 2011). Some people have suggested animation and interactivity as a means to aid model acceptance, increase stakeholder engagement, and improve the usability of discrete event simulations in manufacturing contexts (Chwif et al. 2015). Research has discussed the integration in terms of smart factories and in continuous improvement strategies (Turner et al. 2016). Kuljis et al. (2001) suggest the integration of these approaches can allow users to focus on salient patterns otherwise unnoticed by simulation analysts which would (1) strengthen the understanding of the process and contributing factors, and (2) incorporate latent processes not identified prior.

3.5 Virtual Reality for Facility Review

Virtual reality environments are capable of displaying realistic, immersive, and interactive virtual facilities which support both individual and group understanding (Van Der Land et al. 2013). Virtual reality has been used as a tool for integrated project team members to communicate effectively (Liu et al. 2014). Kumar (2013) developed an experienced based design virtual prototyping framework. In this study, a modeled virtual environment of a future facility was developed to serve as the backdrop to specific important workflow scenarios (e.g., nurse finds crash cart). Both structured and unstructured tasks were deployed in this system. Structured tasks were found to provide more in-depth design feedback from healthcare professionals, yet both were found helpful in engaging staff feedback into the design process. Physical mockups are more common than virtual mockups. In a survey of healthcare industry members on recent projects, 60% of projects were reported to have used some evidence-based design practices and 55% of projects engaged facility staff through physical mockup reviews. However, only 33% of projects used 3D models and 17% used simulation software (Burmahl et al. 2017).

3.6 Summary of Related Work

There has been extensive research into various domains of simulation for process improvement in the healthcare domain. The investigation revealed three operations research techniques in healthcare: layout optimization, process simulation, and virtual visualization (Figure 4). For each of these areas, there are at least two types of categories. For optimization, there are exact mathematical methods and heuristic methods. For simulation, there are optimization via simulation methods, discrete event simulations, and simulation-visualization methods. For visualization, there are specific scenario visualization or unstructured, explorative methods.

4 DEVELOPMENT

Several researchers have proposed a simulation-optimization approach in healthcare settings that take into account distances as well as stochastic input variables, such as processing times and arrival times (Arnolds and Nickel 2015) and walking times (Vahdatzad and Griffin 2016). Another hybrid simulation technique proposed the integration of simulation among different departments and scales of a healthcare facility, including interdepartmental connection, health demographics connection to DES inputs, and human actors (Djanatliev and Meier 2016). Instead of focusing on scales of the healthcare system, we focus on the implementation of a hybrid simulation approach in different facility phases which then could be connected to various scales during operations.

Acar et al. (2009) presented a framework for integrating uncertainty into a generalized mixed integer programming (MIP) optimization through simulation scenario testing. This methodology was later revised by Arnolds and Nickel (2015) where it was proposed with QAP. See Figure 5 for the steps in the hybrid modeling technique using QAP or MIP optimization and discrete event simulation. The steps in the

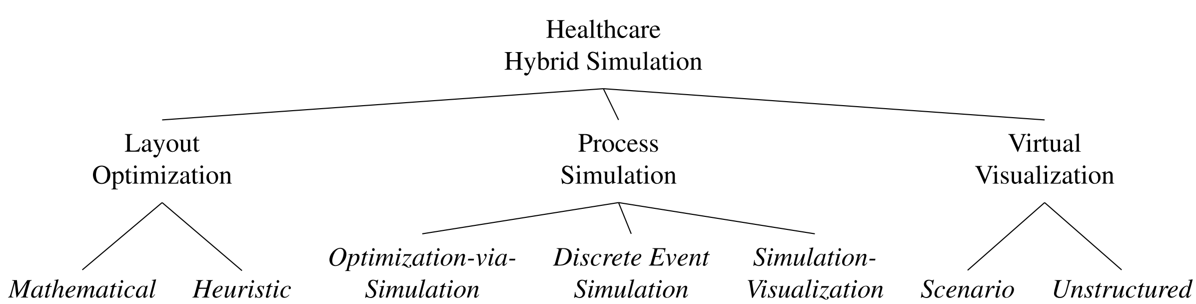

Figure 4: Diagram of hybrid simulation hierarchy proposed for healthcare.

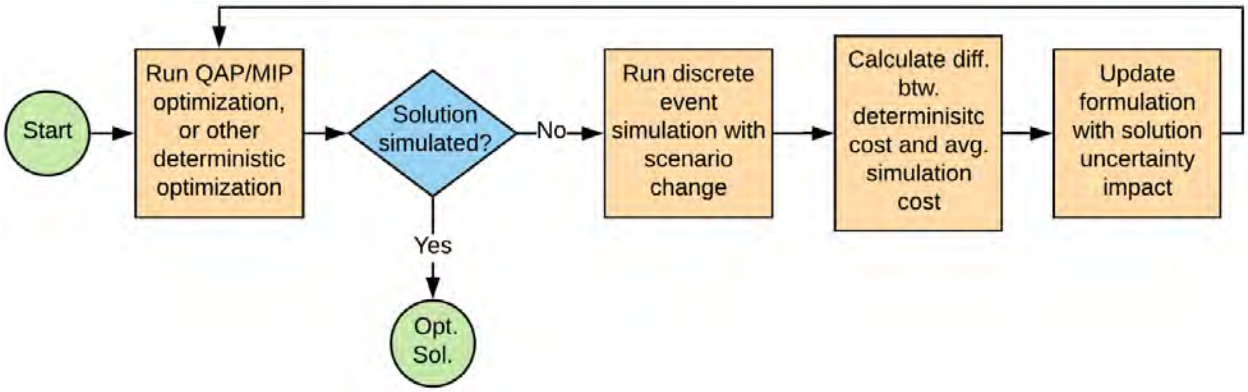

Figure 5: Integration technique proposed by Acar et al. (2009) and revised by Arnolds and Nickel (2015).

modeling framework are: (1) run MIP/QAP optimization to minimize cost or distance; (2) run discrete event simulation with updated workflow scenarios and calculate the difference between the simulated objective value and the deterministic optimization value; and (3) update the MIP/QAP with the function uncertainty difference.

4.1 Healthcare Design Review Process

Engaging healthcare practitioners in the design review process can be difficult. From scheduling to having the correct information available, to guiding the discussion toward the design decisions that are important to make at the time of the meeting, there are many human factors that come into play. When discussing schematic design options, healthcare practitioners struggle with understanding 2D plans and question how operations will occur in a new facility. In fact, 2D representations of spatial problems have been shown to provide insufficient information for design evaluation (Van Der Land et al. 2013). Integrating simulations of the healthcare processes for operations and the spatial configuration can help healthcare practitioners have the information they need, or at least understand the impact of uncertain processes, at the time of their decision.

4.2 Conceptualization

Conceptualization of this hybrid simulation approach started with reviewing the relevant literature, next creating an initial framework, and then observing the planning process in a recent healthcare project. Limitations exist in current hybrid simulation approaches for healthcare, such as time to evaluate a solution, healthcare provider trust in solutions, and challenges for input data collection. By not taking into account some of the main limitations of adoption, simulation-optimization approaches may stay inaccessible to key decision makers and the staff adapting to managerial changes. We propose integrating virtual visualization to aid healthcare provider understanding of the system and aid the simulation-optimization connection to the design review process (Figure 6).

Typically healthcare professionals have not made final decisions about their new processes in early design phases and may be open to major process changes throughout construction. Thus, these are unknown and take a long time for a department to formalize and create consensus. The concept behind the hybrid approach is based on how the inputs and outputs from optimization of layout, simulation of processes, and visualization of the simulated and optimized environment (i.e., the design) can be used for a meta-model for design and implementation. The conceptually integrated approach is shown in Figure 6 where each DES iteration goes through a scenario development in a visualization platform. First, the initial configuration of a healthcare department is optimized given initial flow cost weights, next a scenario testing is conducted of the proposed processes in that version of optimal layout arrangement. Next, the system is virtually

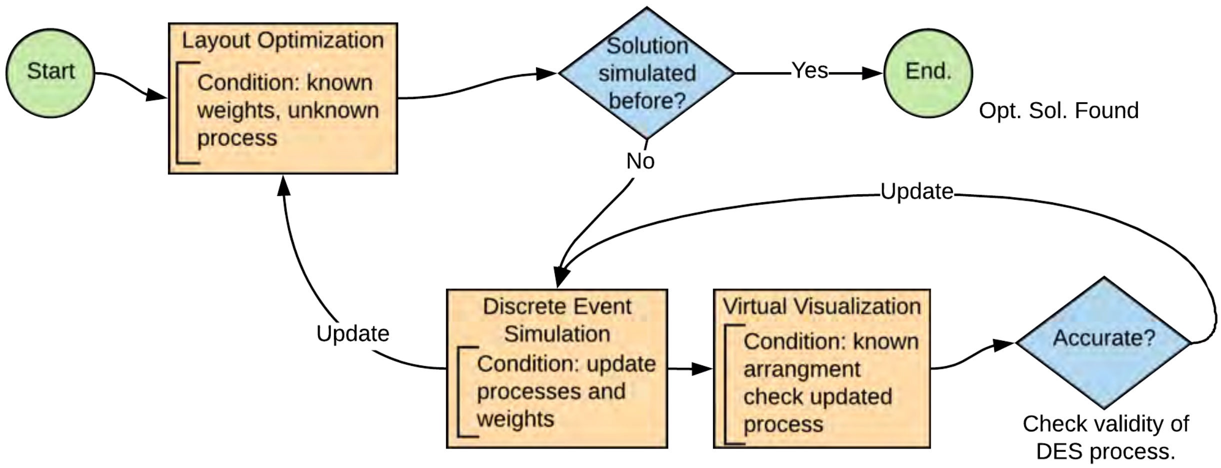

Figure 6: Conceptual diagram for integration of optimization, simulation, and visualization for healthcare planning.

visualized for validation and review of layout and process plans. Next, the new simulation is updated with increased knowledge of facility processes. The new flow cost weights are calculated and input into the optimization and then reevaluated for the simulated and validated scenario change. Once a stable healthcare layout and process combination are achieved, the process comes to a stopping condition and the optimal layout is found for various healthcare processes.

4.3 Hybrid Simulation Objectives

For healthcare facilities to manage the design and operation in an integrated approach, we propose various objective scenarios for practical use of a hybrid optimization-simulation-visualization framework throughout the various stages of facility development: manage, planning, designing, construction, and operations. We expect this list to develop and grow as the technology used is tested and becomes easier to deploy. These simulation objectives include:

- *System understanding and investigation.* During management of a facility, develop an understanding of the system for stakeholders (owner, manager, or staff) including bottlenecks and dynamic impacts.
- *Scenario planning and testing.* During planning, test different patient and healthcare workflow scenarios.
- *Layout option analysis.* During planning and design, test different layout options in conjunction with patient and healthcare workflows.
- *System checking.* During operations, check implementation success, tune processes, and check healthcare practitioner implementation.
- *Sensitivity analysis.* During design and construction, test if newly proposed changes of layout or procedures will impact important healthcare outcomes. During manage and planning, test different layout options and workflows to see how robust a design is for future changes.

5 FACILITY LIFECYCLE IMPLEMENTATION

In this section, we present an illustrative case study of the use of an integrated OSV hybrid approach in various typical stages of the operations and design of a hospital department. While researchers may want to investigate different scales of a health system, such as the macro-level (i.e., dynamic health demographics) or the micro-level (individual actor level), we will focus on a meso-level, e.g., the workflow in a single healthcare department. In the example, we discuss the application of the OSV approach as it applies to specific phases of a project. Since managing a facility occurs at all phases of a project, management specific implementation would be a combination of a selection of these. Design is divided into three common phases: conceptualization, schematic, and development.

5.1 Implementation during Operations

During operational phases of a facility, understanding the current status of performance measures is important. If simulations were performed during planning, a comparison of the simulation model can be performed with real-life conditions to check if the simulation model performed as expected and check if the current operations are following the planned workflows. Tracking current operations can provide more accurate data for finding implementation problems, proposing new workflow solutions, and as a method to collect more accurate input data for future simulations. Corrections to both the simulation and the actual operations can occur. Virtual visualization can be used to help train and communicate motivation of reasoning for operational changes. The model can be used to explore scenario tests of minor functional changes, e.g., adding an additional medication dispensary, moving a registration desk location. More extensive scenario tests can be done in the hybrid simulation environment for nurse and doctor scheduling, logistics, or treatment planning.

5.2 Implementation during Planning

During planning phases of a facility, it is important to understand the future needs of a facility. In this phase, forecasting healthcare demands can help determine the stationary resources needed (bed capacity, location, layout) and thus the capital investments needed to meet those needs. The hybrid simulation approach can be used to test how sensitive a layout configuration is to different healthcare forecasts in order to determine space and layout requirements. Additionally, departments can test different patient and healthcare workflow scenarios to test that objectives of performance measures are being met in the plan before moving forward with a new facility, a redesign, or an expansion.

5.3 Implementation during Design Conceptualization

In the first stage of design, design conceptualization is performed to create configurations and massing models of a program defined from the planning stage. A hybrid simulation approach can be used in this phase of a project to perform room assignments problems, un-equal area optimization problems, and configuration testing in the context of proposed future processes. During this phase, configuration optimization can be performed with roughly determined area requirements and configuration constraints can be formulated. Initial processes should be formulated and tested.

5.4 Implementation during Schematic Design

Schematic design is the phase of a design where different design options are configured and compared. Using a simulation-driven approach, the design team can perform "what-if" scenario testing of a range of design configurations with constraints formulated in design conceptualization. Sensitivity analysis can be performed when faced with uncertain future processes to help understand how different healthcare procedures and policies would, with the layout decisions, impact performance measures of interest.

5.5 Implementation during Design Development

After layout configuration and scenario testing is performed and an optimal layout solution for the various future processes under consideration is selected, detail design development can occur. During this phase, details of the architectural and engineering design are developed. Major changes to layout should be avoided. In this phase, confirmation of room specific requirements and configurations can be developed.

Scenario tests can be refined with additional information on workflow processes to perform design checks. Equipment specification and structural requirements may impact layout configurations and the hybrid simulation approach can be used to perform design checks of changes.

5.6 Implementation during Construction

Once a facility is under construction, it can be very costly to make design changes. However, changes can and will occur on the jobsite. The role of this hybrid simulation in the construction phase of a project can be to check that changes to the approved design do not impact projected facility processes. In addition, minor changed can be made as healthcare practitioners finalize their future proposed workflows. Construction has its own set of complex processes, schedules, and layout planning, which potentially can leverage a similar hybrid simulation approach to the construction layout, processes, and visualization. Additionally, in future developments of a hybrid simulation approach, it may be possible to dynamically, or close to dynamically, make design changes with less impact on the construction schedule, cost, and quality, through automatic updates of design drawings, conflict recognition, and system checking.

6 CONCLUSIONS

There is a large amount of simulation research in healthcare processes and an increasing desire from healthcare managers to increase the efficiency of operations. However, these simulation techniques usually keep the stationary facility elements as static resources. With an aging healthcare infrastructure, redesign is more common, which makes these stationary elements less static than expected. Given that, we found a surprising amount of literature for healthcare layout optimization problems and department-level discrete event simulation, but not enough discussion on how these techniques can be implemented effectively in the design of healthcare facilities. One avenue which is promising is through incorporating virtual visualization in the review process. Further research is needed to develop test-cases and validate this approach. If implemented effectively, it may provide an approach to help disparate groups communicate and come to common decisions on effective and efficient healthcare facility planning and use. We presented a hybrid simulation approach for implementation in the healthcare lifecycle which aims to integrate the facility elements and the healthcare processes. This approach combines layout optimization, process simulation, and virtual visualization in an iterative optimization-simulation-visualization (OSV) framework to be deployed in various states of a healthcare facility: manage, plan, design, construct, and operate. The goals of this approach are two-fold: (1) integrate static facility elements into process simulation as changeable features to aid redesign and planning efforts, and (2) integrate dynamic visualization into the optimization and simulation processes to ensure adequate review of assumptions in models and increase stakeholder buy-in. Five different objectives for the framework usage were identified and presented: system understanding and investigation, scenario planning and testing, layout option analysis, system checking, and sensitivity analysis. The OSV framework provides an initial approach for use in domains where there are a large number of stakeholders (such as healthcare setting) and implementation depends on buy-in from disparate groups of individuals. The framework can be used by researchers to extend simulation-optimization in connecting performance measures in the design and construction phases of projects.

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