Modeling and Evaluation of Circular Layout Facility in Hospitals

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Abstract

Hospitals encompass an intricate infrastructure with a broad collection of practical units of medical forces. A fine planned facility layout planning is necessary for the smooth performance, in addition, to affording protected and suitable services to patients at the exact point in time. The paper proposed an optimized new facility unidirectional circular pathway of patient movement for achieving better health outcomes. The proposed layout would effectively avoid face-to-face contact of arriving and leaving patients inside a hospital, thus maintaining social distancing to avoid the spread of diseases or infection and hurry up the service deliverance method. A qualitative study was conducted for observing various movements of patients and health service providers inside existing hospital layouts, and semi-structural interviews were conducted to identify various issues of the existing infrastructural layouts inside hospital settings. The performance metrics considered included time, the distance between patients at various interaction points, and the capacity of rooms. The proposed layout was compared with the spring layout and random layout to evaluate the efficiency of the proposed system. This circular design proves to be an extremely suggested design to ensure social distancing in a pandemic or during the spread of infectious diseases.

Keywords : **hospital layout planning, circular layout, unidirectional pathway, linear programming, social distancing**

JEL Classification Codes : C0, C6, I0, I1, O0

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In modern years, there has been an increase in the count of studies focused on layout planning of healthcare facilities. The style can be elucidated by the mounting attention in healthcare operations management research as sufficient physical arrangements are vital for the efficient and effective provision of medical service delivery (Benitez et al., 2019). Hospitals with dedicated departments require the interacting units to be located intimately within limits to diminish chaotic and zigzag movements. A well-planned hospital layout design will certify the finest superior service at the least cost, affixing elevated significance to human protection and health (Di Sarno et al., 2019).

People approaching a hospital frequently move through a bunch of investigations before attaining the real target (Prato et al., 2019). Typically, a patient has to approach the reception or an emergency section of the hospital on entering the hospital. Only after that their wants will be concerted. Many times, there can be a set of waiting and delay in such set-ups (Wolf et al., 2017). It is seen that to catch up a definite department, people unintentionally

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take round-about way (Greene et al., 2020), risking catching other diseases in the procedure of reaching the destination department (Meddings et al., 2019). The frontline health care professionals also face stress in managing the patients throughout the process of service delivery (Tiwari & Bhagat, 2021). Patients admire hospitals that reduce their movement within the hospital infrastructure and offer hassle-free action in minimum time (Advani & Fakih, 2019). A computational method for automatically producing an optimal layout choice in a new hospital facility affords a methodology requiring data to build information modeling authoring programs and offers insight into expert perceptions of utilizing an automated approach to support layout design (Lather et al., 2020). There are numerous techniques discussed, but no effective layout is specified to practice social distancing among patients visiting a hospital. Hence, the study draws up relevance, especially in this pandemic situation.

The potential contribution of the paper is as follows :

- A unidirectional circular layout applying linear programming is presented to automatically generate hospital room layouts that reduce the risk of social distancing issues between patients.
- Specifically, linear programming is adapted to optimize features of multiple real-world hospital issues, including time, the distance between patients at interaction points, and the capacity of room or interaction points.
- A brief computational study to demonstrate the effectiveness of the proposed layout based on comparison with other layout designs.

Literature Review

Layout planning involves the arrangement of units in the best possible way within a facility space to minimize distances and associated capacity between interaction units. There are similar studies in alignment with this objective. Passenger need analysis was conducted, and airport facilities were planned accordingly (Gupta et al., 2016). Infrastructure facility is one of the five-core hospital service quality dimensions that contribute to satisfaction and needs to be addressed to enhance patient satisfaction (Krishnamoorthy et al., 2016). Pillai (2021) focused on developing a facility functional layout that promotes convenience, comfort, and economy with enhanced quality of medical care. Small workspaces inside a hospital can create difficulty in social distancing among healthcare workers and patients (Ellsworth et al., 2020). A trail of patient association is to be planned for improved health conclusion, particularly while there is an enormous patient's inflow in search of information regarding the option of healthcare amenities and succeeding medical interest. Both private and public sector hospitals need improvement to address social distancing (Singh et al., 2020). Physical distancing can be improved by rearranging various infrastructural medical facility service delivery stations and also by encouraging additional safer avenues at a safer distance (Keller et al., 2021). A circular hospital facility layout with a unidirectional flow can successfully prevent face-to-face progress of arriving and leaving patients and their bystanders, thus avoiding the spreading of diseases and hastening the service delivery procedure.

Chraibi et al. (2019) proposed mixed-integer linear programming models to find optimal layouts under three different design variants. Each variant has different demands for personnel, patients, and technologies over a planning horizon. Operating facilities can switch functions at reorganization costs from one period to another to meet the altering demands. The common purpose consists of two sub-objectives: the first sub-objective is to reduce the total summation of the reorganization and travel costs, while the second sub-objective is to exploit the whole summation of required nearness amid facilities. Chaeibakhsh et al. (2021) formulated a gradient-free controlled optimization model to reconfigure the hospital space layout to weaken the danger of falls. A limitation was the guarantee of the functionality of room layouts in compliance with architectural strategies. Parsia and Tamyez (2018) introduced the significance of the healthcare facility layout plan and its significance in providing quality medical services. Appropriate layout designs will reduce various types of risks and increase customer satisfaction with improved service quality. Li et al. (2020) developed space planning and organization in hospitals with integrated discrete-event replication and agent-rooted simulation to inspect diverse layout designs. The constructed simulation models described the patient flow and patient needs. Simultaneously, onsite surveying and observing data in addition to practical medical information were employed as inputs. The simulation models measured the patient flow and patient behavior.

In common, layout planning aims at arranging organizational units inside a building such that the available area is used optimally and total distances are minimized. The formation of circular/ring configuration is approved from the traffic loop notion of the 1930s (Benitez et al., 2019) that were commenced to restrain the people in the track and thus preserve effectual unstoppable passage. There is an exit for every department and the frequent resource at suitable extents. The circular form aids simple admittance and non-overlapping run trail, eradicating needless connections that assist in saving time for a variety of patients, medical workers, and former supplies. Additionally, it assists the flow of patients in a solitary track only so that they can penetrate from one track and depart throughout a new in its place of turning about the entire mode reverse to the entrance point.

Research Methodology

The objective of the research paper is to develop an optimization model for a unidirectional circular facility layout design using linear programming (LP) aimed to maximize the distance between patients at various interaction points to enable maintaining social distancing in a hospital.

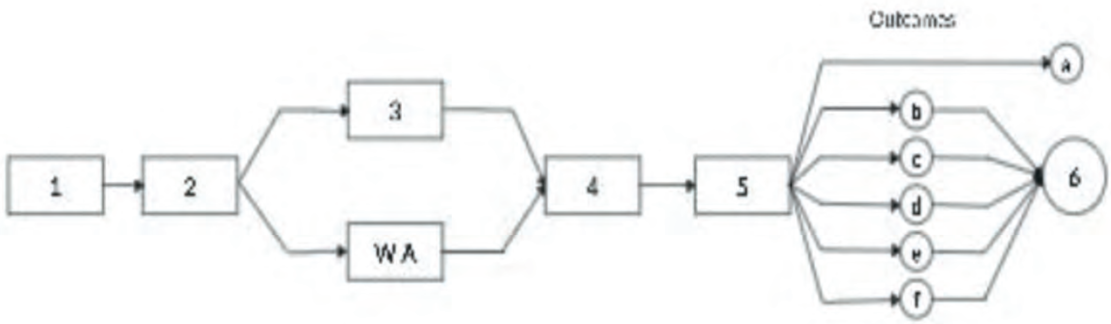
For collecting data, the mixed methodology is incorporated. Qualitative analysis was done with observations relating to outpatient movements and further quantified by conducting semi-structured interviews over three months (April – June 2020 in Kerala). A qualitative study in the form of observations aided in identifying the movement of patients entering a hospital for medical assistance and the time taken at various interaction points for delivery of service. The linear programming model is employed to maximize the distance between patients at various interaction points along with the capacity of the room. The analysis is carried out using Python language using the NetworkX module in Windows 64-bit operating system. The new proposed circular unidirectional design with LP facility is limited within the scope of out-patient interactions and movements. Inpatients and casualty interactions and movements are excluded.

The decision points and the outcomes concerning interaction points in the hospital and the typical patient movements are shown in Figure 1. Initially, the patient approaching a hospital enters the reception counter, which issues a token directing towards the consulting room area (Decision 1). The patient goes to the consulting area utilizing the counter available there to register or renew the registration and gets into the queue line/ waiting areas to the consulting room (Decision 2). Few patients may use restrooms (Decision 3). Preliminary examination and patient's health status are recorded by the health care staff (Decision 4). Patients then enter the consulting room and get examined by the doctor(s) (Decision 5). After consultation, various patient movements are represented as outcomes. Few of the patients leave after consulting (Outcome a), few patients move to labs after making necessary payments and return to consulting rooms with lab test results or wait at the waiting area for instructions (Outcome b), few patients move to pharmacy counters for buying medicines (Outcome c), few patients go to room admission department (Outcome d), few patients visit the canteen (Outcome e), and few patients are redirected to other consulting rooms (Outcome f). Finally, at Decision Point 6, all patients leave the hospital through different exits or unique exits.

Linear Programming (LP) Model for Unidirectional Circular Facility Layout

Various interaction points or rooms identified in a hospital includes registration counter (R_1, R_2,...,R_k), which is centrally located, consulting rooms where general patient check-ups are carried out, pharmacy counters, laboratories, canteens, restrooms, room admissions, other consulting rooms like X-ray rooms, MRI scan, etc. (oCR_1,oCR_2,...,oCR_n). All interaction points have their unique exits so that no patients will get overlapped while exiting the hospital.

Figure 1. ***Decision Points and Outcomes of Interaction***



The linear programming model is employed to maximize the distance between patients at various interaction points along with the capacity of room formulated as in (1) and (2):

$$Distance = d_1 + d_2 + ... + d_n \quad (1)$$

$$Capacity = c_1 + c_2 + ... + c_m \quad (2)$$

The distance between patients at interaction points is denoted as d, the total number of patients in the hospital is denoted as n, c is the capacity of a single room, and m is the total number of rooms in the hospital.

Analysis and Results

Computational Results

The section describes the results of the proposed unidirectional circular layout using linear programming in hospitals. The performance metrics comprise the distance between patients at interaction points, the capacity of the room, and time. The analysis is done using Python language using the NetworkX module in Windows 64 - bit operating system.

Algorithm 1 : Unidirectional Circular Layout with Linear Programming

	Objective : To maximize the distance between patients to enable maintaining of social distancing
1.	Begin
2.	Set the initial distance between patients at interaction points as 0
3.	For I in range (0, length (distance between patients at interaction points))
4.	Distance between patients at interaction points = initial distance between patients at interaction points + distance between patients at interaction points [*i*]
5.	End for

6.	Set the initial capacity of rooms as 0
7.	For *j* in range (0, length (capacity of rooms))
8.	The capacity of rooms = initial capacity of rooms + capacity of rooms [*j*]
9.	End for
10.	Determine start time
11.	Determine end time
12.	Average optimized time = start time – end time
13.	end

The patients entering into a hospital enter through the counter and then move to other interaction points like consulting room, restroom, lab, pharmacy, canteen, other consulting rooms, etc. The patients in the consulting rooms can move to other interaction points or exit through the left hospital interaction point. The patients in the restroom can move to other interaction points or exit through the exit interaction point. The patients in the lab can move to other interaction points or exit through the exit 1 interaction point. The patients in the pharmacy can move to other interaction points or exit through the exit 2 interaction point. The admitted patients can move to other interaction points or exit through the exit 3 interaction point. The patients in the canteen can move to other interaction points or exit through the exit 4 interaction point. The patients in other consulting rooms can move to other interaction points or exit through the exit 5 interaction point.

Table 1. ***Number of Patients in Different Interaction Points***

List of all Interaction Points	‘Counter,' 'Consulting room,' 'rest room,' 'Leave hospital,' 'lab,' 'pharmacy,' 'room admission, ' 'canteen,' 'other consulting room,' 'exit,' 'exit1,' 'exit2,' 'exit3,' 'exit4,' 'exit5'

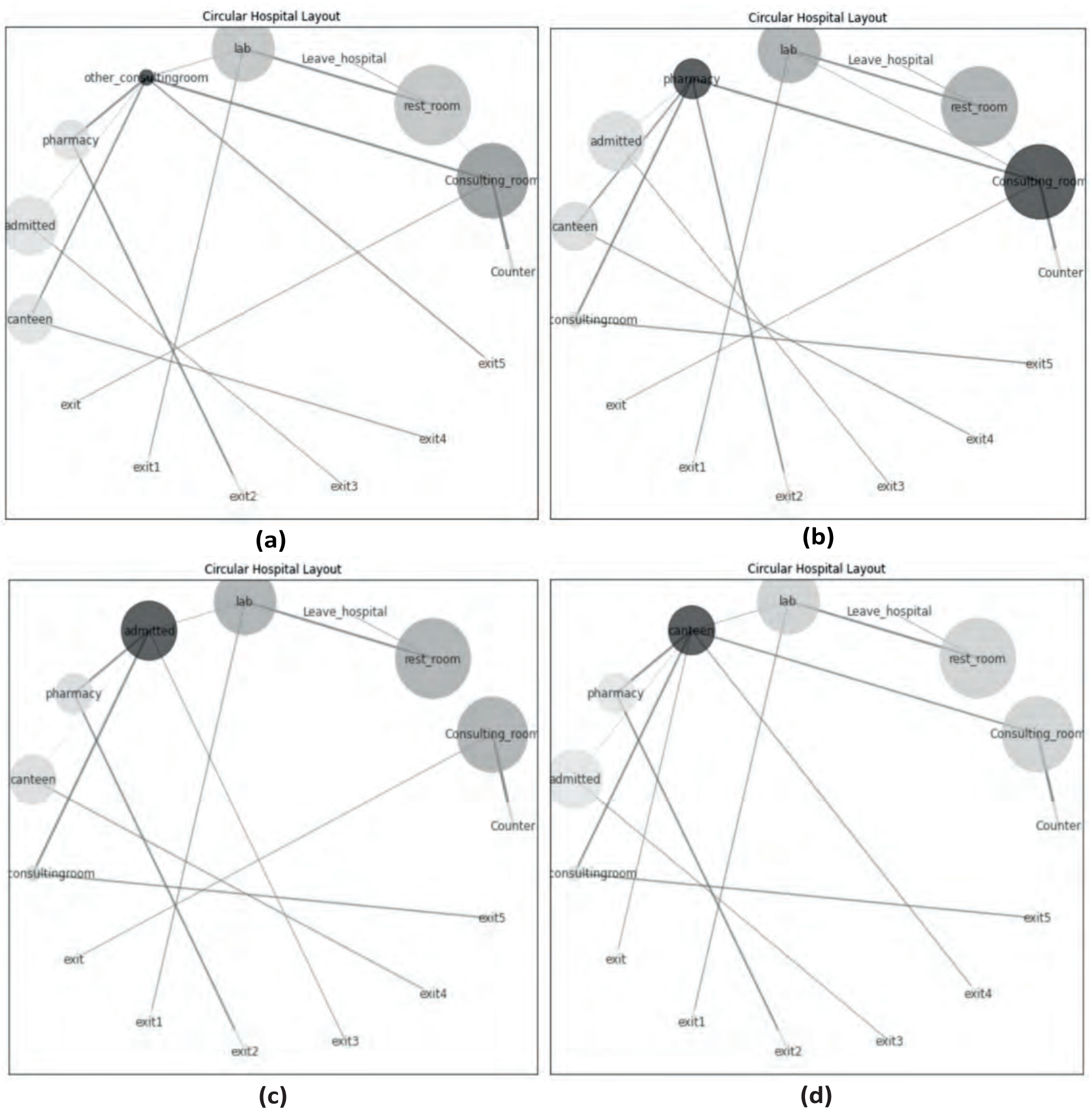
Table 2. ***Number of Patients in Different Interaction Points at a Time***

	Number of Patients			
Interaction Points	**Layout 1**	**Layout 2**	**Layout 3**	**Layout 4**
Counter	1	1	1	1
Consulting Room	4	5	3	3
Restroom	3	3	3	3
Leave Hospital	1	1	1	1
Lab	3	3	3	3
Other Consulting Room	6	2	2	2
Pharmacy	2	5	2	2
Room Admission	2	2	5	2
Canteen	2	2	2	7
Exit	1	1	1	1
Exit 1	1	1	1	1
Exit 2	1	1	1	1
Exit 3	1	1	1	1
Exit 4	1	1	1	1
Exit 5	1	1	1	1

For clarity, four different layouts based on patient movements are considered, and the results are described. The 15 interaction points considered for analysis are tabulated in Table 1. The number of patients in each interaction point at a time in the proposed unidirectional circular layouts is tabulated in Table 2 and is replicated in such a way that for each layout, the number of patients at each interacting point varies. The number of patients in specific interaction points is replicated as to how many times the corresponding interaction point is called. Also, all the interaction points have a unique exit rather than a common exit, thus reducing the contact of patients.

The unidirectional circular layout of the four mentioned layouts is pictorially shown in Figure 2. From the figures, it can be noticed that the connections between interaction points vary due to the movement of patients from time to time. However, in the interaction points such as counter, leave the hospital, exit, exit 1, exit 2, exit 3, exit 4, and exit 5, the values are constant, that is, 1 all the time. This is because only one patient is identified at the hospital's entry and exit from all interaction points.

Figure 2. ***Circular Unidirectional Flow with LP in Hospitals (a) Layout 1 (b) Layout 2 (c) Layout 3 (d) Layout 4***



The distance between the patients in the interaction points, the room capacity with the number of patients in the room/ interaction points can hold, and the movement of patients between interaction points are illustrated in Table 3. The distance between patients at various interaction points is estimated in units, one unit to be taken as 10m. In this case, it is considered that only one patient occupies a room, but the total capacity of the room is given individually for four different layouts and finally the total. The linear programming mathematical operation is done to determine the total distance between the patients and the total capacity of the room.

Table 3. ***Number of Patients in Different Interaction Points***

Layout	Distance of Patients Between Interaction Points	Room Capacity	Interaction Point Connections
Layout 1	3.0465	2243.3395	[('Counter,' 'Consulting room'), ('Consulting room,' 'rest room'),
	0.2325	5503.9175	('Consulting room,' 'other consulting room'), ('Consulting room,' 'exit'),
	2.2425	6221.1865	('rest room,' 'Leave hospital'), ('rest room,' 'lab'), ('lab,' 'other consulting room'),
	0.9391	478.676	('lab,' 'exit1'), ('other consulting room,' 'pharmacy'),
	0.8565	4218.3375	('other consulting room,' 'admitted'), ('other consulting room,' 'canteen'),
	2.2380	1562.229	('other consulting room,' 'exit5'), ('pharmacy,' 'exit2'),
	0.6660	3404.985	('admitted,' 'exit3'), ('canteen,' 'exit4')]
	1.1595	2340.5435	
	2.136	230.234	
	0.3645	418.8685	
	1.812	599.2455	
	1.476	2233.8985	
	1.9485	20.0085	
	1.0185	480.7935	
	1.2315	480.7935	
Total	**21.3675**	**30437.0565**	
Layout 2	2.8965	2243.3395	[('Counter,' 'Consulting room'), ('Consulting room,' 'rest room'),
	0.2175	5503.9175	('Consulting room,' 'lab'), ('Consulting room,' 'pharmacy'),
	0.651	6221.1865	('Consulting room,' 'exit'), ('rest room,' 'Leave hospital'), ('rest room,' 'lab'),
	2.115	478.676	('lab,' 'exit1'), ('pharmacy,' 'admitted'), ('pharmacy,' 'canteen'),
	0.915	4218.3375	('pharmacy,' 'other consulting room'), ('pharmacy,' 'exit2'), ('admitted,' 'exit3'),
	0.8715	1562.229	('canteen,' 'exit4'), ('other consulting room,' 'exit5')]
	2.088	3404.985	
	1.140	2340.5435	
	0.3645	230.234	
	1.6620	418.8685	
	2.0925	599.2455	
	1.8	2233.8985	
	1.02	20.0085	
	1.215	480.7935	

	1.4775	480.7935	
Total	**20.526**	**30437.0565**	
Layout 3	3.0015	2243.3395	[('Counter,' 'Consulting room'), ('Consulting room,' 'rest room'), ('Consulting room,' 'exit'), ('rest room,' 'Leave hospital'), ('rest room,' 'lab'), ('lab,' 'admitted'), ('lab,' 'exit1'), ('admitted,' 'pharmacy'), ('admitted,' 'canteen'), ('admitted,' 'other consulting room'), ('admitted,' 'exit3'), ('pharmacy,' 'exit2'), ('canteen,' 'exit4'), ('other consulting room,' 'exit5')] ('canteen,' 'exit4'), ('other consulting room,' 'exit5')]
	0.1875	5503.9175	
	0.915	6221.1865	
	0.8415	478.676	
	2.208	4218.3375	
	0.6960	3404.985	
	1.1415	1562.229	
	2.13	2340.5435	
	0.162	230.234	
	2.22	418.8685	
	0.96	599.2455	
	1.875	2233.8985	
	1.2	20.0085	
	1.4415	480.7935	
Total	**18.9795**	**30437.0565**	
Layout 4	2.7465	2243.3395	[('Counter,' 'Consulting room'), ('Consulting room,' 'rest room'), ('Consulting room,' 'canteen'), ('rest room,' 'Leave hospital'), ('rest room,' 'lab'), ('lab,' 'canteen'), ('lab,' 'exit1'), ('canteen,' 'pharmacy'), ('canteen,' 'admitted'), ('canteen,' 'other consulting room'), ('canteen,' 'exit'), ('canteen,' 'exit4'), ('pharmacy,' 'exit2'), ('admitted,' 'exit3'), ('other consulting room,' 'exit5')]
	0.2025	5503.9175	
	1.6620	6221.1865	
	0.8265	478.676	
	2.178	4218.3375	
	0.726	2340.5435	
	1.1445	1562.229	
	2.19	3404.985	
	0.3645	230.234	
	1.9425	418.8685	
	0.9450	599.2455	
	1.215	2233.8985	
	1.875	20.0085	
	0.99	480.7935	
	1.44	480.7935	
Total	**20.448**	**30437.0565**	

The four layouts describe different movements and their corresponding distance and capacity. The total distance between the interaction points estimated through linear programming for the first, second, third, and fourth layouts is 21.3675, 20.526, 18.9795, and 20.448, respectively. Also, the average capacity of the room estimated through linear programming for the first, second, third, and fourth layouts is 30437.0565, 30437.0565, 30437.0565, and 30437.05650, respectively. The distance between patients at each interaction point varies in each of the four layouts as the movement of the patients to different interaction points varies from time to time. Subsequently, the capacity of the room is identified as the same for all four layouts as the hospital capacity will not change and will remain constant in all-time instances.

Comparison of Unidirectional Circular Layout in Hospital with Other Layouts

The comparison of the proposed novel unidirectional circular layout in the hospital is compared with the spring layout and random layout to identify the effectiveness of the proposed layout. The pictorial illustration for the spring layout and random layout for an existing hospital layout is illustrated in Figure 3 and Figure 4.

From the figures, it is clear that the patient movement at interaction points overlaps to a great extent in both layouts. Further, the comparison values of the three layouts are tabulated in Table 4.

Figure 3. ***Unidirectional Spring Layout***

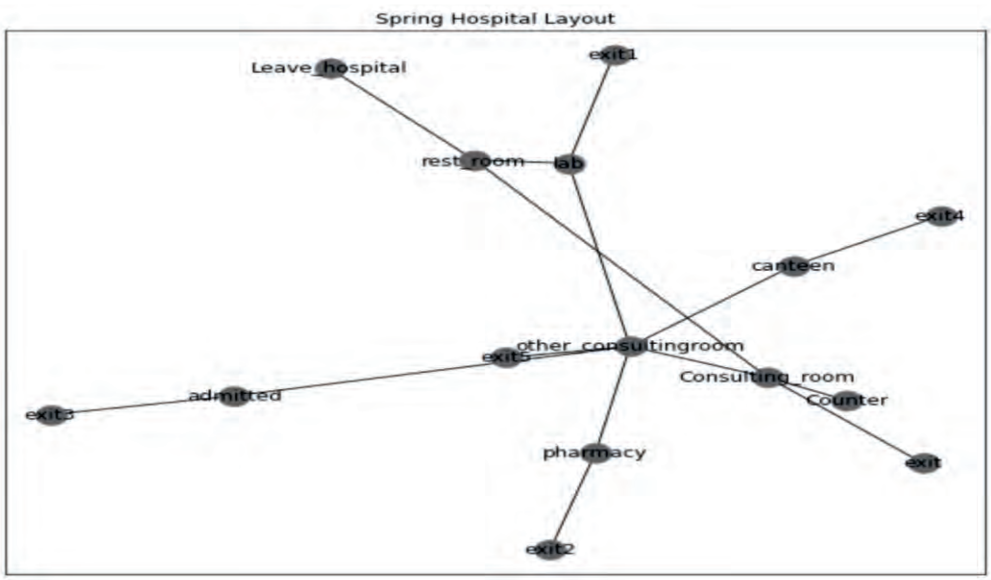


Figure 4. ***Unidirectional Random Layout***

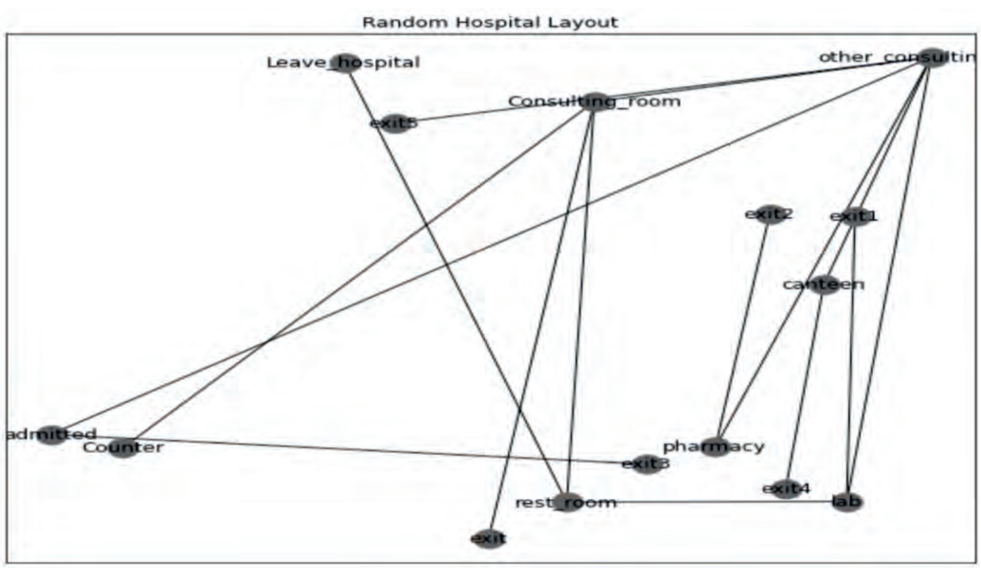


Table 4. *Comparison Between Circular Layout, Spring Layout, and Random Layout*

Layout	Performance Metrics	Circular Layout	Spring Layout	Random Layout
Layout 1	**Total Time**	0.3158	2.2590	0.7588
	Total Distance	21.3675	19.943	18.5184
	Capacity	30437.0565	24349.6452	18262.2339
Layout 2	**Total Time**	0.1703	2.2169	1.1400
	Distance	20.526	19.1576	17.7892
	Capacity	30437.0565	24349.6452	18262.2339
Layout 3	**Total Time**	0.1074	1.7791	0.8905
	Distance	18.9795	17.7142	16.4489
	Capacity	30437.0565	24349.6452	18262.2339
Layout 4	**Total Time**	0.06365	1.7124	0.7235
	Distance	20.448	19.0848	17.7216
	Capacity	30437.0565	24349.6452	18262.2339

The total time taken by the patient to complete the medical procedure using the listed interaction points in the first layout for circular, spring, and random layouts is identified as 0.3158, 2.2590, and 0.7588, respectively. Consequently, the time parameter for the proposed circular layout is low in all the interaction points of the other three layouts. This proves that the proposed circular layout takes the least time compared with the spring layout and random layout, thus proving the proposed layout's effectiveness. The distance between patients at various interaction points is compared, where the average LP distance in the first layout for circular, spring, and random layouts is identified as 21.3675, 19.943, and 18.5184, respectively. The distance between patients at various interaction points for the proposed circular layout is found to be higher when compared to all other layouts. These comparisons show that the distance among patients at various interaction points is higher for circular layout, enabling social distancing practices that are most critical in this current pandemic situation.

The capacity of the room or the interaction points remains constant in all the layouts, identified as 30437.0565 for circular layout, 24349.6452 for spring layout, and 18262.2339 for random layout. The hospital capacity for the proposed unidirectional circular layout holds more patients than the spring layout and random layout. This proves that the proposed circular layout offers a high capacity (space) for a hospital, thereby enabling effective social distancing among patients.

Managerial and Theoretical Implications

Most layout planning applications occur in industrial environments. When optimizing manufacturing facilities, the main objective is to minimize traffic areas and traveled distances. Hospital layout planning is characteristically positioned on a planned decision level as consistent information about the movements of patients throughout health checking is essential. However, not only the planning of new hospitals is considered, but also the reconstruction and improvement of existing ones are considered. An existing hospital is allowed to fix facilities at its location by fixing variables. There is an exit for every department and the frequent resource at suitable extents. Progress of patients is severely clockwise with no zigzag movements, that is, unidirectional, like in product layout to the coverage probable. Considering the topography of the infirmary, the chief block ought to be the essential cynosure and the other departments as separate entities associated with the instant neighborhood.

An external chain road akin to the outline of a ring is built to bond the departments to assist more liberated people's movement, processes, and operations. The ring unites each department and opens a separate sub-channel p in and out of all departments, thus building the hypothesis shift from the conventional functional layout, which runs a congested, unpredictable people movement. Thus, the traffic intensity is extremely guarded as the movement flow is firmly unidirectional.

The arriving patients do not hinder the flow of departing patients and diminish the probability of illness as well. Patients don't acquire a possibility to spot other suffering patients face to face, thus augmenting their mental health. Doctors and paramedical workers discover it trouble-free to shift about with effortlessness and advance the speed of cure. A patient incoming a particular department leaves after treatment after online payment from the department itself, equivalent to droplets of water exiting in a centrifuge. This diminishes congestion in the mainstream flow. Traffic and congestions in hospitals can be evaded and are extremely necessary for the existing circumstances (a pandemic situation similar to COVID-19). This circular design proves to be a highly suggested design to ensure social distancing in a pandemic or during the spread of infectious diseases.

Conclusion, Limitations of the Study, and Scope for Future Research

In the research paper, an effort has been made to recommend a new optimized unidirectional circular facility layout design in hospitals using a linear programming model for guarantee social distancing, which is critical in the existing circumstances of COVID-19 spread, and additionally, the advantages of the new facility notion of layout design are analytically investigated. The proposed layout is compared with other layouts such as spring layout and random layout to prove the effectiveness of the proposed method. All the parameters such as time, the distance between patients, and the capacity of the room for the proposed method are found to be better than other existing layouts. The proposed unidirectional circular layout can be a solution to address the issues of extended waiting hours for medicinal notice and further managing the spread of the disease during an epidemic. Thus, this novel layout design judges social distancing, patient safety, and health-improving general output.

The unidirectional circular layout benefits an even flow of facility action, thus producing superior ergonomics, even though the facility is limited within the scope of out-patient interactions and movements. Inpatients and casualty interactions and movements are excluded. This can be considered as a scope for future research. The unidirectional circular movement trail design for patients is offered as a perfect candidate for an effective hospital layout, thereby reducing the confusion in managing volume and interaction points in patient progress.

Authors' Contribution

Dr. Sini V. Pillai conceived the idea and developed qualitative and quantitative design to undertake the empirical study. Mr. Abhilash V. S. extracted research papers with high repute, filtered these based on keywords, and generated concepts and codes relevant to the study design. Dr. Sini V. Pillai verified the analytical methods and supervised the study. Both the researchers conducted the interviews, some in colloquial language and some in English. The same were further transcripted and translated into English. The numerical computations were done by Dr. Sini V. Pillai using Python language by means of the NetworkX module in Windows 64-bit operating system and wrote the manuscript in consultation with the co-author.

Conflict of Interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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