Digital Twinning for Productivity Improvement Opportunities with Robotic Process Automation: Case of Greenfield Hospital

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***Abstract*—Hospitals of the future need to embrace new, disruptive, and innovative technologies, and prudently consider the cost of such technological investments to ensure that the technologies can interface well with human operators, without the high financial commitment. Such hospitals look to improve operational efficiency and productivity to be able to treat more patients without increasing cost and justify the capital investment. Put simply, the hospital staff will in future co-work and collaborate with robotic technologies in a shared workspace to deliver the same level of patient care if not better. For this to happen, there is a need to appreciate how the current human effort can be integrated seamlessly with Robotic Process Automation (RPA) activities in a hospital setting and to visually show to the operations/logistics personnel the attendant challenges/ bottlenecks. We study a Greenfield hospital in Singapore and provide a digital twin of its future operations with RPA solutions. Specifically, we design an efficient logistics system (central sterile services, materials management, food, pharmacy, linen), develop robust RPA solutions, and minimize the disruptions from automation introduction. The transportation system within the hospital, dispatching rule of the lifts and robots, are optimized through extensive simulation.**

***Index Terms*—digital twinning, simulation, hospitals, logistics, Singapore**

I. Introduction

The population of many countries around the world is rapidly ageing. An ageing population would bring challenges to the healthcare systems around the world through the increased share of elderly citizens and chronically ill patients as well as a greater demand on the supply side of a hospital to deliver faster, better, and cheaper bedside care if possible. There is thus a need to strengthen healthcare services for the elderly and the sick, both now and into the future [1]. As such, there is an imperative for the healthcare system to innovate, work smarter on all levels, leverage on innovative practices used in the other sectors, and lift the level of productivity. Hospitals in this regard need to consider ways and means to improve the operational efficiency and workflow in order to be able to treat more patients without increasing cost and complexity, and justify the capital investment made [2]. In the hospital of tomorrow, Robotic Process Automation (RPA) will be a part of the Internet of Things (IoT) to assist the new mission [3, 4]. Put simply, ancillary service workers, e.g., porters and nurses will in future co-work and collaborate closely with smart robots (umeebots) in a shared workspace to deliver the same level of patient care if not better. Robotic equipment will replace the more labour-intensive, repetitive low value-added, mundane rule-based tasks that need to be attended to in any hospital such as linen delivery within a hospital, food service to the wards at regular meal times, consumables such as adult diapers, and prescription labelling and dispensing of medication to the patients. For this to happen, there is a need for a deeper and richer understanding of how the human effort can be integrated seamlessly with the RPA activities in a hospital setting and to visually show to the operations/ logistics personnel in a healthcare institution the attendant challenges/ bottlenecks, even before a hospital is built [5].

This paper presents a case study of a greenfield large hospital of 1,800 beds, 8 medical towers of 7 levels each, joined by a common ground floor and two basement levels. The basement levels, B1 and B2, will encompass the full suite of transport and logistics related activities of receiving, storage, preparation, re-supply and distribution. As a part of Singapore's smart nation initiative, the hospital under construction is planning its future operations reality with RPA solutions. The primary objective is to design an efficient supply chain system, develop robust RPA solutions and minimize the disruptions of automation introduction [6]. To run this efficient supply chain system in the future, the operation details have to be optimally designed and sufficiently twinned through digital advances such as virtual simulation [7]. Capital budgeting wise, the main concerns are the best number of self-guided vehicles and trolleys, which determine the volume of the investment, the minimum number of docking stations for the vehicles, accommodating the time windows associated with the delivery and return sequences for each department, etc. Further, the transportation system inside of the hospital, dispatching rule of the lifts and vehicles, associated with

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the interaction of the self-guided vehicles and patients and visitors should be carefully design and optimized.

To achieve this objective, a large complex system of supply chains inside of the hospital is constructed and optimized. A new framework of simulation and optimization for the supply chain system is proposed. The main components of the work include the RPA solution development, 3-D building information collection, supply chain simulation and optimization, and resource based scenario analysis. Behind every design and goal towards operational efficiency in hospital, lies the distribution of physical supplies of pharmaceuticals, surgical medical products, medical equipment, sterile items, linen, and food. Addressing the initiative behind the “smart hospital of the future”, the case hospital expected to start its operations in 2022 will house a variety of state-of-the-art medical facilities. This greenfield project will adopt smart technology and minimize the resource deployment through process simplification and workflow automation.

The rest of this paper is set as follows. Section 2 describes the problem. Section 3 presents the approach taken. Section 4 highlights the simulation, assumptions, and parameters used while Section 5 shows the results, together with the scenario analysis. Section 6 concludes.

II. Problem Discription

Distribution vehicles within a hospital take on many forms such as the pneumatic tube system used to transport lightweight goods including clinical samples and pharma drugs, robotic porters for ad-hoc demand, and automated guided vehicles (AGVs) for the delivery of meals to the wards, as shown in Fig. 1.

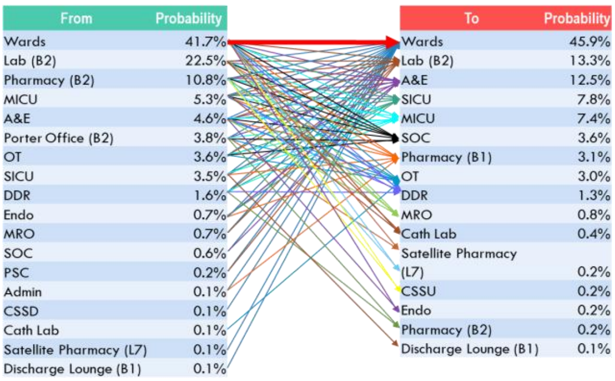

Figure 1. Ad-hoc deliveries among individual departments (data provided by hospital).

This paper outlines the approach and provides an in-depth discrete event simulation model through SIMIO for the deployment of an AGV-based internal distribution network for five key supply chains in a hospital: food, pharmacy, linen, materials management (MM) central sterile services (CSS), coupled with other supplementary chains such as afternoon tea and ad-hoc meals. We will describe the problem as follows.

Food: Food operations in the 8-towers, 9-storeyed hospital serve three meals and an afternoon tea to the patients daily, delivered by the AGVs from a central kitchen located at basement B2 to the wards according to a fixed schedule and patient demand data. The AGV schedule for the delivery and return of the food trolleys is given by the end users, based on experience. The food trolleys are prepared well before the scheduled delivery time, placed in the queue at the dispatch station of the kitchen area before an AGV picks it up for transport. The AGVs will drop off the food trolleys in the lobby of the designated wards for rethermalization [1] prior to consumption. The collection of the food trolleys follows a specific time-window and the AGVs will pick the food trolley from the AGV lobby of each floor and return to the trolley return area of the B2-kitchen. The logistics flow matrix of the daily meal transport and delivery is verified by the end users and a copy is available on request.

Pharmacy: The distribution of prescription drugs/medication to the different departments and wards in the hospital, are also dispatched in trolleys from the main store in the basement to the end users by the AGVs according to the daily demand and schedule. The daily demand and delivery schedule are presented to the team by experienced pharmacists. Before the scheduled time of the delivery, the pharmacy trolleys are prepared according to the demand of the Facility Planning Units (FPUs), transported to the AGV dispatch station in queue for the AGVs to pick up before being dropped off at the respective receiving bays of the destinations. The return of the pharmacy trolleys also follows a specific time window where the AGVs will collect the empty trolleys from the AGV lobby and return to the trolley return area of the pharmacy.

Linen: We study the delivery of the linen items to the wards, operating theatres (OTs), and emergency departments. According to the daily demands, the linen trolleys are prepared in the B2-linen department and the same AGVs are used to deliver the items to the designated destination. For operational efficiency, we have divided the daily demand of linens into two AGV delivery-trips (50 in the morning and 49 in the afternoon) and used two different time windows for serving the different FPUs. The daily demand of linen in terms of the linen trolleys, as well as the delivery and return times are confirmed by the operations staff. As the linen and MM departments share the same AGV dispatching area, it is deemed critical for the scheduling arrangement for both supply chains to avoid any conflict in schedules and potential congestion of the basement corridor, which may delay the time to distribute the items. The linen trolleys are prepared before their delivery times, set in the dispatching queue for the AGVs to pick up, before transporting to the various FPUs. The details of the logistics matrix for linen are again verified by the end users and a copy is available on request. The return of these trolleys also follows a set time window for pick up and return, to the trolley return area of the linen store.

MM & CSS: The MM department responsible for delivering the required patient consumables such as nappies, bandages, tissue, bandages, works closely with

[1] Rethermalization of a food trolley takes about 45 min.

the CSS Department (CSSD), which manages the sterilization of the used medical equipment and supplies. Due to the lower volume of the individual demands, the MM are consolidated with the CSS items before being dispatched out to the FPUs. The materials are delivered by the AGVs from the main store at the basement level B2 up to the FPUs on different floors according to the demand data and schedule. The daily-consolidated demand for MM & CSS with time windows for delivery and return are summarized by the end users, who also highlighted an expected optimal number of AGV trips associated with the time windows.

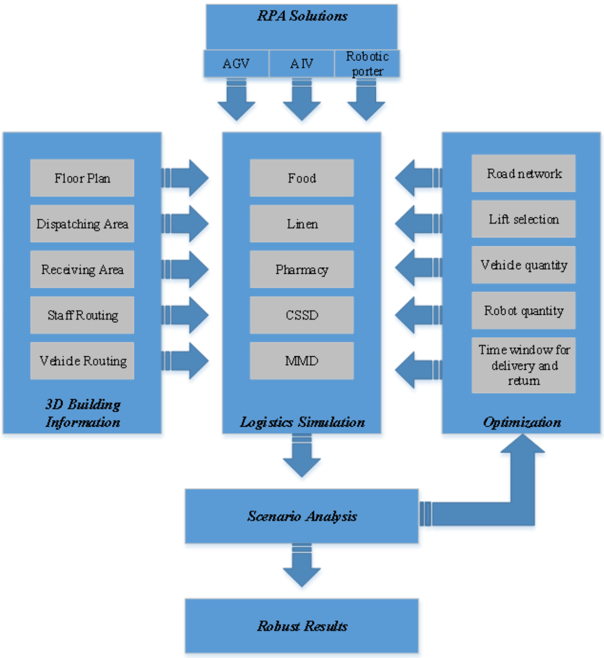

Figure 2. Framework of simulation and optimization.

Separate trolleys within the CSSD are used to handle the clean and dirty surgical items. The demand for clean trolleys with time windows for delivery and return summarized by the end-users. Through SIMIO, we found that the optimal total number of trolleys to be used (and therefore to purchase) is 26, and the demand comes from the acute care ward, dental centre, emergency department, and specialist outpatient clinics. Through running the SIMIO model, the scheduled time for dirty trolley return and clean trolley delivery are optimized within the integrated model considering all the five supply chains. The specific locations and demand of each department are confirmed with the end-users.

Supplementary transport chains: Apart from the five main supply chains mentioned, this case study also looks at three supplementary chains to anticipate the operations and workload of the hospital [8], namely,

i. Ad-hoc deliveries by robotic porters
ii. Afternoon tea to wards in levels 4 to 6 of hospital tower 5, and levels 5 to 7 of tower 6, planned for a Phase 2 opening
iii. Delivering personalized consumable and linen items to patients who may require more than one change a day for surgical reasons.

The logistics matrix for the afternoon tea and magic box is set up as requested by the end-users. Due to this randomness, the historical data of similar ad-hoc deliveries in the other hospitals are collected and summarized. Based on this historical data, the probabilities of each location as a start point and end point are summarized and shown in Fig. 2. With inputs from the hospital's planning team, the demand of the future hospital's operation was estimated. It was found that 175 random robotic porter trips are assumed within 24 hours for the 1,800-bedder hospital.

III. Method

In building the digital twin of the future hospital, properly develop robust RPA solutions and to minimise the disruption from the automation solutions, a new framework of simulation and optimization for the hospital logistics and transport system is proposed. The main components include the RPA solution development, 3-D building information collection, activities and flows simulation and optimization, and scenario analyses. The details of the key parts are confirmed with the end-users. The following steps illustrate the sequence of conducting the study:

3-D building information: The features of the main building and the Specialist Outpatient Centre (SOC) both comprising nine levels respectively are constructed in the simulator. The layout details include the logistics dispatching area, receiving area, lift entry, ward location, lift location, and docking stations. These indicate the start and end-points of each delivery route along with the connections between them, which are essential for the simulation. The robotics routing can be determined so that the workflows for each supply chain are established.

Robotic and automation solutions: Therefore we have developed reasonable solutions where RPA represents the automation solutions, including AGV application for heavy load delivery (150-200 kg), robotic porter for ad-hoc and small items distribution (≤ 20 kg), and other technologies like RFID.

Simulator: Simio ver. 9.0, an event-based simulation software, is used to design the operation details. All the supply chains are simulated with the recommended automation solutions along with the assumptions and parameters. For example, the trolleys are assumed ready before the scheduled time. The simulation was thoroughly designed so that the internal road network of the hospital infrastructure is well planned. The historical data from the other hospitals and assumptions serving as the inputs for each supply chain are then ported into the simulator.

Optimization and results: To enhance transportation efficiency, the internal traffic should be optimized, especially at the lifts and the basement. For example, traffic directional rules were set, such as all the automated vehicles travel on the left, and different priorities are allocated to different lane branches at any junction or crossing. The queue lines at the dispatching areas for food and linen are re-organized to avoid congestion at any junction and or at the lift landings of each tower. The utilization rates of the lifts and AGVs are calculated and the key scenario analyses for extreme situations conducted. The results obtained from the simulation were then used to determine the optimal number of AGVs, robotic porters, and trolleys for purchase by the hospital.

Through these steps, the automation solutions for the hospital can be developed and validated based on the virtual simulator, without incurring heavy expenses. Robust results in terms of the number of vehicles and the utilization analyses of lifts and vehicles can be obtained.

IV. Simulation

In this study, the simulation objectives are to observe and predict the future operation by importing the pre-designed solutions, identify the deviation of the existing against the simulation results, and to optimize the logistics and transport workflow performance. The supply chain details in terms of the trolley preparation, AGV selection and response, route choice and lift scheduling can be simulated realistically. The delivery and return of the trolleys of each chain are scheduled and optimized in the simulator. The key characteristics of the supply chain system including the vital parameters or assumptions, which have a large time impact on the system, should be decided before starting the simulation.

A. Parameter Setting and Assumptions

Before proceeding further, it is instructive to highlight some of the key assumptions made and parameterize the simulation setting accordingly.

The AGV and robotic porter are two types of vehicles used within the hospital, which have a large impact on the performance of each supply chain and their interactions. The speed of the AGV and robotic porter motion is 1 m/s in reality, but we set it at 0.5 m/s to represent the worst-case scenario considering the uncertainty of unforeseen breakdowns and foot-walkers' disruption along the corridors. It is also assumed that the AGVs and robotic porters can automatically load/unload the trolleys at the specified locations. The times for loading and unloading are both set at 10 sec. For the ad-hoc delivery with the robotic porters, additional time is required for the staff to collect the payload, so a delay allowance of 2 to 15 minutes is allocated in the simulator for this, to compensate for the busy-ness of the workday. The AGVs and robotic porters will select the shortest path to the destination automatically.

Although it is assumed that all the trolleys are fully equipped before delivery, it is necessary to define the trolley offload and reload times when computing the number of trolleys in use. The offload and reload times are set to 15 minutes respectively, based on anecdotal evidence and personal communications with the staff.

The lift, as another critical transportation bottleneck in the supply chain system, also determines the transportation system efficiency; its speed is set as 1 m/s. In order to simulate fully movement reality, the acceleration and deceleration of the lifts are set as 0.6 m/s^2. Further, only one AGV can be transported by one lift at any one time. Whenever a vehicle arrives at a lift selection node in each tower, it will check for the availability of both lifts in that tower using IoT. If both lifts are available, we will assume that a lift will lesser utilization for that day will open. Otherwise, an available lift will open. Likewise, if both lifts are busy, all vehicles will wait at the node.

In particular, to reflect realistically the flexible meals demand from the wards, the order table is developed in Simio. Further, the category of food type for each bed is listed for each ward. Three columns are allocated to each bed, indicating the bed occupancy, and halal, and non-halal food requirements. If the bed is occupied, the food requirement has to be indicated, else it is taken that the bed is idle (no patients). With that, the total number of halal and non-halal meals will be tallied, and the number of food trolleys will be automatically aggregated more importantly, if the ward is idle, the checkbox option in front of the bed from that ward is left blank, and no trolleys will be delivered to the ward.

V. Findings and Results

Various scenarios of three parameters are considered in this paper to check on their impact on the hospital's daily operation: 1) the number of lifts for each tower; 2) patient demand in terms of meals; 3) to share or not to share the SOC lifts with the public.

Lift in each tower: Two lifts are allocated to each tower, making it total of 16 lifts for 8 towers. Initially two lifts are simulated for each tower. However, this yielded a very low utilization of the lifts. Therefore, it is necessary to test whether one lift is sufficient to meet the transportation requirement. Two scenarios were analysed: two lifts per tower and one lift per tower. For the scenario with one lift, the path to another lift is removed when running the simulation. In short, the AGVs and robotic porter can only use one lift. The peak period of breakfast delivery from 05:30 hours to 06:30 hours is taken as an example.

The results of the two scenarios in terms of the lift trips and utilization are summarized for the end-users to use. Regarding the lift trips, the number of lift trips for the one lift scenario is doubled compared to two lifts scenario and so the lift utilization. As there are also ad-hoc deliveries, the lift utilization or trips will increase linearly. In addition, due to the different demands from each tower, the lift trips and utilization rates will vary.

From the simulation results, all the deliveries can be completed on time with one lift. The maximum lift utilization in this scenario is less than 75% during peak periods. Hence, it is reasonable to conclude that it is feasible to assign one lift to each tower for transport.

Food trolley: As the number of patients varies over time, the demand for daily meal delivery will change accordingly. The maximum demand for food trolley per ward is 3. However, a ward is never fully occupied all the time. Hence, we tested the scenario with 2 trolleys per ward as well.

The number of AGVs required is the key parameter. To visualize the number of AGVs in use, a display board is developed. The number of AGVs in use can be monitored in real time when running the simulation. For example, the number of AGVs after 05:30 hours increases significantly as it is the delivery time for breakfast. All the AGVs are needed to complete the food delivery within the one-hour time-window. By running the simulations for a day of 24 hours and verifying the simulation log of the transporter, the maximum number of AGVs required to complete the food delivery task is 26. For the case with two trolleys per ward, the maximum number of AGVs needed is 21. This represents a reduction of 19.2% in the number of AGVs needed.

SOC lift: Due to the limited number of lifts in the SOC building, it is necessary to explore the possibility of lift sharing by the AGVs and the public. First, the approximate lift capacity is calculated. In the simulator, the peak hour and the number of trips of the lift are recorded. Taking the lift in tower 1 as an example, its peak duration of work is 169.68 minutes from 05:00 hours to 20:00 hours, and the number of trips is 207. Each lift trip takes 0.818 minutes on average. The same calculation can be conducted on the other lifts. The maximum among all the average values is 0.93 minutes. Therefore, it is safe to assume that the average travel time per trip is 1 minute after adding some relaxations such as the time for the lift door to open, wait, and close.

Denoting the lift capacity as the most number of trips that can be covered in one minute, the lift capacity per hour for all 7 levels can be assumed as 60 trips. From 05:00 hours to 20:00 hours, the total lift capacity is 15*60 = 900 trips. In addition, the lift utilization at the selected period expressed as lift-utilization = lift-trips/900. For the SOC lift, with an average maximum utilization of 20.33% from 05:00 hours to 20:00 hours, this suggests that there is room for lift sharing between the AGVs, robotic porters, staff, and visitors.

A. Key Results

Using the simulation model and running several scenarios, we were able to optimize some of the decision variables such as the lifts, AGVs, and robotic porters. Further, we determined the best output for the delivery time windows for each supply chain and found the delivery sequence in which there was no congestion or bottlenecks present. Specifically, we highlight some of these results for performance measurement and benchmarking.

Specifically, running and testing the scenarios over a busy period in a day, a week and over a month, it was established that 26 AGVs, and an additionally 2 AGVs as spares were recommended for purchase. This would have incurred a cost of 26x$150,000=$3.9 million.

Similarly, it was determined that the new hospital would require 15 robotic porters. This information is useful for the hospital procurement to go to market to source for the right number of robotic porters. Likewise, in terms of the number of trolleys used for transportation in all the five supply chains, the simulator results suggest that the food supply chain required 106 food trolleys; for linen, the morning delivery needs 50 trolleys while afternoon delivery needs 49 trolleys; for MMD, CSSD and pharmacy it is 64.

VI. CONCLUSION

Introducing the simulated RPA solution steps into a hospital's operation can thus help to circumvent potential bottlenecks. The simulation model depicts the key characteristics, behaviour, and functions of the selected system, enabling it to reflect the operation reality of the system over time, without incurring heavy expense. The new framework of simulation and optimization for a logistics and transport system can be applied to future hospitals and or other industries dealing with the operational logistics aspect, and relying on the approach of digital twinning to reduce building cost, operational uncertainties, and tight budgetary constraints [9].

Several learning points are instructive for sharing. First, only the essential factors such as the lift, corridor, dispatching area, locations of each department, and wards are required to be included when designing the actual 3-D building model. Second, there should clear traffic rules to regulate flow and govern behaviour. For example, dedicated paths lift and unloading bays are required for the AGVs. Doing so will to avoid disruptions from the foot-walkers and shorten delivery time. Third, the robotic porters, through proper governance measures, should be able to travel along dedicated pathways to deliver specific items up to the patient's bedside. Fourth, the location of the central dispatching or receiving areas should be kept away from busy traffic intersections and/or lift landings as the AGVs queue before a dispatching or receiving area may lead to unexpected traffic congestions and bottlenecks.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTION

LIU, ZHANG, DUTTA, and WU performed the simulation on the each of the five supply chains studied in this paper. All the authors were involved in the data collection, analysis, and results reporting. GOH wrote this paper. All the authors had approved the final version.

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