Development of A Multi-Agent System for Automated Resource Allocation in Maintenance of Hospital Buildings

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ABSTRACT

Development of A Multi-Agent System for Automated Resource Allocation in Maintenance of Hospital Buildings

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Facility managers of hospitals face complex maintenance decisions as they address a multitude of maintenance requests in an environment of limited resources and segmented information. The complex, uncertain, and dynamic nature of the maintenance management environment is a source of concern to facility managers in hospitals due to unexpected failure of building components, the daily arrival of maintenance orders, and changes in related schedules.

Responding to a growing demand for maintenance, on one hand, and lack of proper maintenance management systems, on the other, has led to delays in repair and maintenance of the building components and systems in hospitals. Such delays could cause significant distress to patients and health-care personnel. In such circumstances, centralized systems become inadequate because of their top-down approach which lacks a feedback mechanism and ignores new information. Therefore, to address any change, centralized systems have to be reformulated making it impractical, short-sighted, and problematic to adopt them in hospitals. As such, the use of centralized systems can lead to financial losses and dissatisfaction of patients. It, therefore, becomes necessary to establish a distributed maintenance management system to support the decision-making process of facility managers.

To address the issues stated above, this thesis presents three newly developed automated models (1) a computer resource allocation model for integrating fragmented maintenance information; (2) two simulation models that represent the dynamic environment of maintenance resource allocation; and (3) a Simulation-Based Optimization (SBO) model for resource allocation that minimizes the down-time of building components being considered for maintenance.

Accordingly, this research initially focuses on the maintenance workflow and resource allocation issues pertinent to hospitals. A distributed system is developed to integrate segmented information

at different levels of maintenance management with the aim of minimizing maintenance delays in hospital buildings. Multi-Agent Facility Management System (MAFMS) is conceptually designed as a distributed interactive system. This design employed Unified Modeling Language (UML) diagrams that illustrate the specific agents of the system and how these agents interact with each other.

Two simulation models are then developed to demonstrate the benefits of the developed method in reducing the response time to maintenance requests. The developed simulation models consist of two components: a workflow process model and Resource Allocation System (RAS). A Discrete Event Simulation (DES) is used to simulate the maintenance process flow while a Multi-Agent System (MAS) is used to simulate the process of allocating resources for maintenance activities in hospital buildings. The workflow process is simulated as a DES. The workflow process contains order registration, arrangement, and maintenance tasks distribution (orders). For the RAS component, a Multi-Agent Resource Allocation Simulation (MARAS) is developed to simulate different resource allocation scenarios accounting for interactions among various agents (decision-makers) in the maintenance process. A case example is presented to demonstrate the essential features of the developed method. Maintenance data of a hospital building is used to initiate the multi-agent simulation for workflow management process. The simulation results show the benefits of the developed method, to reduce the response time to maintenance requests. Sensitivity analysis method is used to validate the simulation model.

Finally, the third model, i.e. the SBO model, is developed using OptQuest. This model is proposed to optimize the use of limited resources and reduce the down-time of building services components. The SBO model is validated using the sensitivity analysis method.

Dedicated to my parents and my husband for their endless love and unwavering support.

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LIST OF ABBREVIATIONS

t_{ch}	checking time
fa	failed
mc	maintenance checkup
t_{ma}	maintenance time
μ	mean value
$\mu_{t_{rr}}$	mean repair time
$\mu_{t_{re}}$	mean replacing time
$\mu_{t_{ma}}$	mean maintenance time
$\mu_{t_{ch}}$	mean checking time
μ_{BCA}^{rr}	mean number of BCAs in the “Repair” state
μ_{BCA}^{re}	mean number of BCAs in the “Replacement” state
μ_{BCA}^{mc}	mean number of BCAs in the “Maintenance Checkup” state
μ_{BCA}^{fa}	mean number of BCAs in the “Failed” state
z	mean annual down-time of BCAs
n	number of agents
n_{CMA}	number of CMA
n_{PMA}	number of PMA
n_{TCA}	number of TCA
rr	repair
re	replacement
t_{rr}	repair time
t_{re}	replacing time

ABM	Agent-based Model
ACy	Age Coefficient for facilities
AEDET	Achieving Excellence Design Evaluation Toolkit
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AME	Annual Maintenance Expenditure
BACs	Building Automation Systems
BCAs	Building Component Agents
BEM	Business Excellence Model
BIM	Building Information Modeling
BPM	Business Process Modeling
BPI	Building Performance Indicator
BREEAM	Building Research Establishment Environmental Assessment Method
BSC	Balanced Score Card
CBR	Case-Based Reasoning
CBSE	Component-Based Software Engineering
CCTV	Closed-Circuit Television
CI	Condition Index
CM	Corrective Maintenance
CMA	Corrective Maintenance Agent
CMMS	Computer Maintenance Management System
CMR	Corrective Maintenance Resource
CRT	Current Reality Tree
CS	Controller System
CSFs	Critical Success Factors

C&A	Care and Attention
DB	Database
DBMSs	Database Management Systems
DCy	Density Coefficient for patients in the clinic
DES	Discrete Event Simulation
DSS	Decision Support System
EDMS	Electronic Document Management Systems
EAM	Enterprise Asset Management System
EMS	Energy Management Systems
ERs	Emergency Rooms
ERP	Enterprise Resource Planning
EST	Earliest Starting Time
FIFO	First-in, First-out
FM	Facility Management
FMA	Facility Management Agent
GA	Genetic Algorithm
GIS	Geographic Information System
GP	Goal Programming
GUI	Graphical User Interface
HPR	High Priority Requests
IC	Infection Control
ICUs	Intensive-Care Units
IT	Information Technology
KPIs	Key Performance Indicators
LDA	Loss-Distribution Approach

LIFO	Last-in, First-out
LPR	Low Priority Requests
LST	Latest Starting Time
MAFMS	Multi-Agent Facility Management System
MARA	Multi-Agent Resource Allocation
MARAS	Multi-Agent Resource Allocation Simulation
MAS	Multi-agent System
MCDM	Multi-Criteria Decision Making
MEI	Maintenance Cost Efficiency Indicator
MPM	Maintenance Performance Measurement
MSC	Maintenance Management Span of Control
MSR	Maintenance Sources Ratio
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
MVC	Model-View-Controller
NAME	Normalized Annual Maintenance Expenditure
NHS	National Health Service
NN	Neural Networks
O&M	Operations and Maintenance
ORs	Operating Rooms
PDM	Predictive Maintenance
PM	Preventive Maintenance
PMA	Preventive Maintenance Agent
PMR	Preventive Maintenance Resource
PPVC	Prefabricated Prefinished Volumetric Construction

RAS	Resource Allocation System
RCM	Reliable Maintenance Method
RFID	Radio Frequency Identification
RPN	Risk Priority Number
RRs	Regular Rooms
SA	Supplier Agent
SBO	Simulation-Based Optimization
SD	System Dynamic
SOA	Service Oriented Architecture
SS	Scatter Search
SSO	Single Sign-on
SSS	Service Scheduling System
TBPM	Time Based Preventive Maintenance
TCA	Team Coordinator Agent
TS	Tabu Search
UK NHS	United Kingdom National Health Service
UML	Unified Modeling Language
WRCA	Work Receiver/Coordinator Agent

CHAPTER 1. INTRODUCTION

General Background

The increasing complexity of healthcare facilities is mainly due to growing urbanization (with an elevated demand for healthcare services) and the technological advancement in building components and medical equipment. Currently, hospitals are compelled to provide wider and diverse healthcare services to an increasing number of patients. The deterioration rate of healthcare facilities is typically higher than other buildings and is compounded by the fact that these facilities provide essential services and are occupied and in use 24 hours a day, all year round (Yousefli et al. 2017). Evidence from Canadian hospitals points to a growing volume of deferred maintenance (Alzaben et al. 2014; Beckman 2014; Roberts and Samuelson 2015). Deferred maintenance is the postponement of buildings and equipment upkeep due to limited resources, leading to delays in providing quality services to patients and hospital personnel. This has significant consequences for patients and personnel. In recent years, the annual cost of deferred maintenance to hospitals has been estimated as somewhere within the region of $5B to $35B (Roberts and Samuelson 2015).

Over the years, there has been a growing focus on improving maintenance management practices in hospitals, mainly through establishing maintenance strategies, conducting performance measurements, and employing Information Technology (IT), to address maintenance cost, schedules, and performance targets of hospitals (Amos et al. 2020; Gómez-Chaparro et al. 2020).

Although there has been research concerning maintenance management practices in hospitals, not a great deal of research has addressed the issue of maintenance delays in hospitals. Limited research has been conducted to develop and implement decision support systems crafted to specific needs of maintenance management units in hospitals.

Problem Statement

Inefficient resource allocation, inadequate communication between the Facility Management (FM) department and resources, and ineffective workflow monitoring are among the main issues, which leads to deferred maintenance at semi-public hospitals (Alzaben 2015). Resource allocation is one of the vital functions of maintenance management.

A number of studies expressed the significance of resource allocation and its influence on a hospital's maintenance function. So, inefficient resource allocation can lead to poor performance, time delay, and also cost overruns in hospitals. Hence, one way to prevent and/or reduce maintenance delays, while addressing the issue of deferred maintenance, is by improving the resource allocation process and maintenance workflow management. However, providing a resource allocation plan that takes into account unforeseen events while realizing the near-optimal solution, can become complicated. The current state of research does not fully consider the complex and dynamic nature of the resource allocation in maintenance management of hospitals.

Literature reveals that in a complex facility such as a hospital, a time-efficient and reliable maintenance function relies on advanced communication and information systems (Tuli et al. 2011). However, the information about various maintenance activities is generally fragmented and not well documented nor recorded. Fragmented and incomplete information has a significant impact on communication of the availability of resources and access to required information. On the other hand, centralized systems, which are commonly used in hospitals, are not efficient in solving resource allocation problems, since the solution space grows exponentially by an increase in the number of maintenance activities and resources.

Despite the significant contribution of research to resource allocation in maintenance of hospital buildings, there is limited research focusing on the facility management systems to enhance inter-resource communication by sharing maintenance information among resources. So, it is vital to develop an integrated and distributed resource allocation system to address dynamism in maintenance activities at hospitals. This development would facilitate the tracking of maintenance orders, accelerate the resource allocation process, and update the maintenance schedule to increase the performance of hospitals.

Research Objectives and Scope

The main objective of this research is to develop a method to integrate information at different levels of maintenance management and automate workflow and resource allocation process with the aim of minimizing maintenance delays in hospital buildings. Hospital elevators are considered as the case study components due to their criticality and impact on hospital services and in reflection of reported delays and congestions in hospitals caused by deferred maintenance of elevators in hospitals. As such, other building components such as HVAC, sensing lighting, fire systems, etc. were not included in this research. This thesis focuses on efficient management of elevators; considering their continuous use in 7 days a week / 24 hours per day. Furthermore, highlights the availability of hospital facilities due to their criticality in contrary to common focus on cost in case of conventional facilities. In this sense, the failure analysis proposed in this research resembles the case of other critical facilities and infrastructure such as power plants, hospitals, and etc. This is to be accomplished through development, testing and validations of:

1- Multi-Agent Facility Management System (MAFMS) to reduce maintenance delays by improving the maintenance workflow and resource allocation process;

2- Simulation models including: a workflow process model and a Multi-Agent Resource Allocation Simulation (MARAS) to simulate and analyze workflow and resource allocation process; and

3- Simulation-based Optimization (SBO) model to select the optimal number of resources to minimize maintenance delays.

Another purpose of the developed method is to integrate the workflow management with resource allocation planning, to facilitate the resource adjustments needed in response to dynamic changes and requirements over the entire maintenance process. The scope of this research is limited to applications in hospital buildings. This study focuses on the practice of in-house resource allocation.

One of the main purposes of this system is that it aims at minimizing the response time to failure incidents to minimize the breakdown time of important building facilities and reduce deferred maintenance. In this sense, this study focuses on the practice of in-house resource allocation for the developed MAFMS.

Thesis Layout

This thesis contains six chapters. The structure of the thesis is as follows:

Chapter 2 presents a comprehensive literature review related to the maintenance management of hospitals and identifies research gaps.

The literature review focuses on: (1) maintenance management in hospitals; (2) applications of IT and Decision Support System (DSS) in management of maintenance information; (3) computer simulation methods for maintenance management; and (4) SBO for maintenance management.

This chapter is an extended and modified version of previously published papers titled "Healthcare facilities maintenance management: a literature review" published in *Journal of Facilities Management* (Yousefli et al. 2017) and "Maintenance workflow management in hospitals: An automated multi-agent facility management system" published in *Journal of Building Engineering* (Yousefli et al. 2020) and "Application of multi-agent simulation for maintenance workflow management and resource allocation in hospital buildings" accepted in *Journal of Architectural Engineering* (Yousefli et al., 2021).

The contents of the proposed method are divided into two chapters; Chapters 4 and 5. After an overview of methodology development in Chapter 3, Chapter 4 of this thesis is devoted to the development of MAFMS as the first model. To test the feasibility of the proposed method, two simulation models and optimization model are developed in Chapter 5. This chapter provides a detailed description of the simulation models and SBO model development, results analysis, and model validation.

Chapter 3, describes an overview of the proposed method, which consists of three models, and each model houses a number of phases. The first model focuses on the development of MAFMS. This model has three phases including: (1) proposing a workflow process; (2) developing a multi-agent based resource allocation process; and (3) developing MAFMS architecture for managing maintenance information in an integrated system.

The second model discusses the development of two simulation models. The second model consists of three phases including: (1) data collection through survey questionnaire and interviews with facility managers of hospitals; (2) modeling and simulating the proposed workflow process through the means of DES; and (3) modeling MARAS as an interactive simulation model that considers the workflow and resource allocation parameters. Finally, the third model deliberates the development of the SBO model.

Chapter 4 presents the development process of MAFMS (Model 1). This model automates the workflow and resource allocation process, which reduces the response time to maintenance orders. This chapter includes workflow process development, multi-agent based resource allocation process, MAFMS architecture development. Unified Modeling Language (UML) is employed to define the agent interactions in MAFMS. To illustrate the applicability of the model, a simulation model is developed and the validity of the proposed model is tested in the next chapter.

This chapter is a slightly modified version of the formerly published paper titled “Maintenance workflow management in hospitals: An automated multi-agent facility management system” published in *Journal of Building Engineering* (Yousefli et al. 2020).

Chapter 5 focuses on the development of MARAS model (Model 2), which can simulate dynamic interactions between human resources and building components through the workflow process. This is followed by a case study, which demonstrates the modeling process. This chapter describes the simulation results and provides an analysis of these results.

In addition, this chapter focuses on the development of a SBO model to optimize the selection of resource allocation scenarios while respecting the availability of building components (Model 3). The optimization results are illustrated and the validity of the SBO model is tested in this chapter. This chapter is a slightly modified version of the accepted paper titled “Application of multi-agent simulation for maintenance workflow management and resource allocation in hospital buildings” in *Journal of Architectural Engineering* (Yousefli et al. 2021).

Chapter 6 summarizes the work presented in this thesis, highlights the research contributions, presents the limitations of current research, and suggests future works.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter contains a comprehensive listing of publications and their classifications according to various attributes. Recently published literature focusing on healthcare facilities management and its maintenance management functions is classified into various areas and sub-areas (Alrabghi and Tiwari 2013; Leung et al. 2013; Li et al. 2020; Yousefli et al. 2017, 2020; 2021). In this chapter, the hierarchical framework is proposed to organize maintenance management topics that included maintenance activities, from operational to strategic levels, in typical hospitals. The hierarchical framework explores the impact of those functions on the performance of maintenance activities in hospitals. In fact, improving the performance of maintenance functions in healthcare facilities not only leads to cost and resource efficiency gains but also elevates the satisfaction of patients by increasing the quality and reliability of services.

The demand for healthcare services and facilities is ever increasing in the twenty-first century owing to population growth, increased life expectancies, and elevated standards of life (Hosking and Jarvis, 2003). The growing urbanization has also created the need for more complex hospital buildings. Nowadays, urban hospitals need to provide a diverse set of healthcare services to a vast number of patients and visitors in a more condensed, congested, and concentrated space. This has emphasized the importance of FM in the healthcare sector (CHFM 2016). In this regard, maintenance management is one of the most challenging and costly elements in hospitals (Chotipanich and Sarich 2004; Shohet 2006). It supports the functioning and continuity of care facilities and services of hospitals as critical as emergency and lifesaving care facilities (Shohet et al. 2003). Maintenance might also affect many non-core activities of hospitals such as food storage and supply, cleaning, and security of buildings (CHFM 2016).

National Health Service (NHS) in the UK has advocated the integration of non-core healthcare services under the responsibilities of FM (Amos et al. 2020; Rechel et al. 2009; Rees 1997, 1998). They have identified several issues that are necessary to address to implement an integrated FM in NHS that includes maintenance strategic planning, maintenance benchmarking, customer care, market testing, environment, and staff management (Amos et al. 2020).

A number of studies have been reported in the literature (with mentioning of hospitals and healthcare facilities) on maintenance management issues (Garg and Deshmukh 2006), FM implications (Ventovuori et al. 2007), Key Performance Indicators (KPIs) for facility performance measurement (Lavy et al. 2010) and maintenance performance metrics (Kumar et al. 2013).

Shohet and Lavy (2004) reviewed published literature in the healthcare FM domain. On that basis, they proposed five subcomponents for healthcare FM, including maintenance management, performance management, risk management, supply services management, and development.

Garg and Deshmukh (2006) reviewed the literature for maintenance management and identified several research gaps. In particular, they pointed to the need for customization and implementation of maintenance optimization models in the form of operational DSS, measurement of maintenance performance by considering its links to decisions outside the maintenance unit and integration of IT in maintenance management, just to name a few. Lavy et al. (2010) discussed current measuring metrics and KPIs for FM practices. They classified these indicators into “cost-related” and “non-cost related” or “functional” and “physical” categories. These reviews are capturing the intersection of FM practice and health services that are dealing with maintenance management in buildings in general.

The complexity and criticality of healthcare services highlight the importance of maintenance management function in healthcare facilities. To the best of the authors’ knowledge, no literature review has been conducted with a focus on maintenance management approaches and issues pertinent to hospitals (Yousefli et al. 2017). In this sense, this chapter aims at identifying and organizing available literature in the field of maintenance management for healthcare facilities (Section 2.2). As IT and DSS deal with maintenance issues at all maintenance management levels, a separate section is created to highlight the specific role of IT and DSS in integrating maintenance management information with respect to the peculiarity of issues and complexities in hospitals. (Section 2.3). In this section, different architectures of information systems are introduced and discussed. In Section 2.4, the application of simulation methods as tools to deal with complex problems of maintenance management is investigated. This section provides an overview of the challenges, limitations, and opportunities of different simulation methods for addressing maintenance resource allocation issues.

Finally, Section 2.5 reviews the literature on SBO and Meta-heuristic methods for optimizing maintenance operations. The advantages and challenges of the available methods in the literature are discussed in sections to be the baseline for the proposed methodology of this research.

2.2 Maintenance Management in Hospitals

The study categorizes the literature and adopts a review hierarchy according to maintenance management functions in hospital buildings. The existing literature on maintenance management in hospitals is reviewed and classified into a hierarchy that follows a typical maintenance management process in hospitals. The literature review is organized into a hierarchy (as depicted in Figure 2-1) based on a typical maintenance management process in hospitals. The hierarchical framework is organized into five sections as follows: maintenance strategies (Section 2.2.1), maintenance cost (Section 2.2.2), maintenance workflow and resource allocation (Section 2.2.3), maintenance risk management (Section 2.2.4), and maintenance performance measurement (Section 2.2.5). From the top of the hierarchy of maintenance management activities downwards, from the strategic level to the tactical and operational activities, covers the topics that are established or emerging in the literature. As such, the tactical issues are classified under the umbrella of costing, sourcing, and contract management. The operational aspects are also organized into resource allocation and risk management. This process will conclude at the overarching component of "maintenance performance", where the whole process is monitored and evaluated for performance improvements. So, the literature review section of this study is organized based on the aforementioned hierarchical framework.

2.2.1 Maintenance Strategies

By definition, maintenance is a combination of related administrative and technical activities to maintain equipment, facilities, and other physical assets in acceptable operating situations or to return them to this condition (Muchiri et al. 2011). Shohet and Lavy (2004) have a similar definition of maintenance. In this sense, to achieve a cost-efficient and operationally effective maintenance system, long-term strategic planning for various functions of maintenance is necessary.

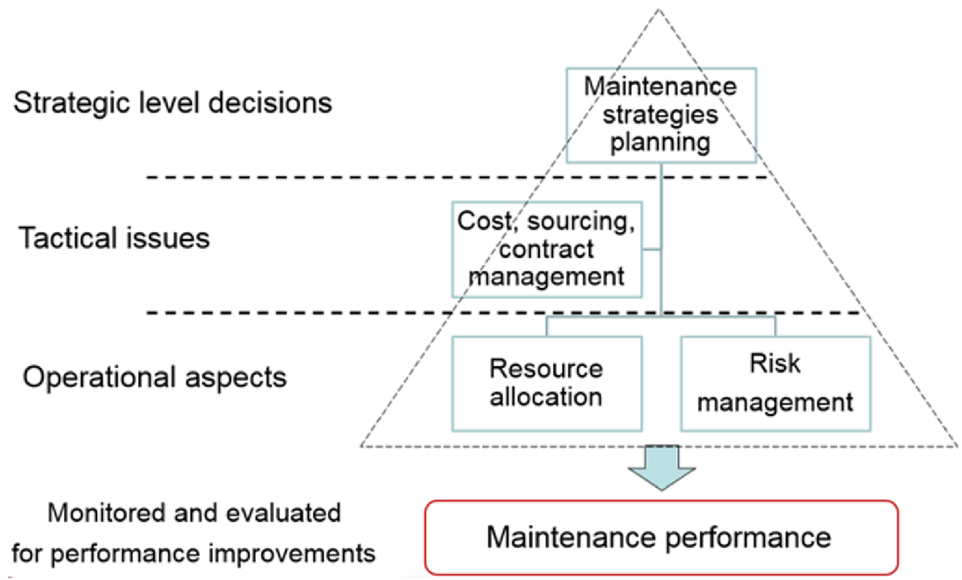


Figure 2-1. Proposed hierarchy of maintenance management.

Since hospitals are complex buildings with a large number of mechanical and electronic systems, choosing the right maintenance strategy has a significant impact on the quality of health care services. Building maintenance strategies are divided into Corrective Maintenance (CM), Preventive Maintenance (PM), and Predictive Maintenance (PDM) (Rani et al. 2015). CM occurs when a component is going out of function and needs intervention in the form of repair or replacement (Hao et al. 2010; Higgins et al. 2002). On the other hand, PM includes planning of periodical repairs or replacements at defined time intervals. PDM monitors the symptoms and likelihood of a failure to make-in-advance maintenance interventions based on these predictive measures (Ben-Daya et al. 2016).

The choice of maintenance strategy in hospitals, as complex buildings (with a lot of mechanical and electronic components, systems, and equipment), is significantly impacted when the maintenance budget is limited. Maintenance budget has been particularly reported as one of the main maintenance-related issues in public hospitals (Alzaben 2015). So, the main factors that dictate the choice of a maintenance strategy are the maintenance budget and criticality (and complexity) of the failure (Ighravwe and Oke 2019).

Mohammadpour et al. (2016) stated that prioritization/categorization of building components based on recorded data on failure incidents and their root causes is the first step toward maintenance (strategic) planning decisions. Au-Yong et al. (2015) highlighted customer satisfaction as another dimension that forms the maintenance strategies in hospitals. They indicated that the performance of maintenance function is impacting and shaping the clients' satisfaction and (public) perception about a hospital. Rani et al. (2015) conducted a customer satisfaction survey in some healthcare facilities. Their findings show that there is a direct relationship between customer satisfaction and maintenance strategies. They indicated that PM should be adopted as a preferred maintenance strategy in hospitals. They highlighted the fact that the maintenance activities with a periodical schedule are more appealing to users of hospitals, including the patients, visitors, and the staff. Owing to its unpredicted nature, in reactive (corrective) maintenance, the human resources might not be familiar with the root cause of the breakdown, which could leads to delays, reworks, disruption of services and an increased cost of maintenance. Gómez-Chaparro et al. (2018) examined the relationship between time spent on preventive maintenance and demand for corrective maintenance, as well as the energy consumption of a hospital building in Spain. Shamayleh et al. (2019) proposed a Reliable Maintenance Method (RCM) for the maintenance of medical equipment. They stated that since the RCM focuses on criticality, it is more effective than Time Based Preventive Maintenance (TBPM). Njuangang et al. (2018) investigated the relationship between FM strategies and Infection Control (IC) in hospitals based on historical data and evidence.

In summary, according to the reviewed literature, the selection of appropriate maintenance strategies in hospitals shapes important decisions in healthcare maintenance management. However, very limited research has been reported on the identification of appropriate maintenance strategies (and linking them to maintenance activities) in hospital buildings. This is considered a major research gap, as the choice of maintenance strategy shapes the tactical and operational decisions in healthcare maintenance management (that will be discussed in the following sections).

2.2.2 Maintenance Cost

Several factors affect maintenance expenditures. Few studies have been identified in the literature that review maintenance costing in buildings, mostly without a focus on hospitals (Kim et al. 2019; Kwon et al. 2020). These studies have shown that the biggest amount of expenditures that occur in the service life of buildings is associated with their operational phase, which includes maintenance activities. In particular, Alzaben et al. (2014) developed a model consisting of the Operations and Maintenance (O&M) cost of hospitals. They identified the source of funding and measured its impact on increasing hospital maintenance costs. Stolavs Hospital in Norway was examined to determine factors affecting its operating cost (Yousefli et al. 2017). It is advocated that the rate of occupancy per bed, age, scale and morphology of hospitals are the factors with greater impact on maintenance costs. Lennerts et al. (2005) suggested an approach to cut down the expenditures and increase the efficiency of healthcare facilities through the analysis of FM processes. They aimed at prioritizing the FM processes in terms of their impact on core activities of hospitals. The FM activities with the least impact will be given the highest priority for cost reduction. Diez and Lennerts (2009) developed a cost estimation model directing the cost/budget allocation for FM services related to operation units of four hospitals in Germany. In particular, they have highlighted and quantified the relationship between the cost of FM services and their observed performance.

A number of studies also highlighted benchmarking as a tool to test and measure the operational and maintenance costs in healthcare facilities (Sliteen et al. 2011). They categorized costs of a healthcare facility into investment costs, O&M costs, and disposal costs. They gathered data on the number of patients and beds, O&M activities, and utilization rate of water, gas, and other utilities. The authors demonstrated the economy of scale on the cost of maintenance, O&M staff cost and cost of utilities. In doing so, they have used cost per bed ratio instead of using cost per square meter of floor area. They showed that the latter has a strong correlation with the expenses mentioned above.

Boussabaine et al. (2012) presented the relationship between bed usage and operational costs in hospitals in France. They have advocated that the gross floor area occupied per bed is the best indicator to forecast the O&M costs in the hospitals. Assaf et al. (2011) identified the factors that affect the cost of maintenance in hospital facilities. They have listed 33 factors that influence maintenance costs in hospitals. These factors were categorized into seven subgroups with separate considerations for public and private hospitals. These subgroups consist of legal requirements, design phase requirements, construction phase requirements, maintenance requirements, projected budget for maintenance activities, expected maintenance performance and the norms and benchmarks in the maintenance industry.

Several studies have tried to calculate or predict the cost of hospital maintenance with a limited maintenance budget. Lavy and Shohet (2007) developed an integrated FM model, to predict maintenance costs, performance, and risk, of facilities in hospitals. Salah et al. (2018) proposed a Reliability-Centered Maintenance (RCM) approach to optimize the maintenance inspection time, minimize downtime, and minimize the maintenance cost of medical gas systems, elevator systems, and HVAC systems in hospitals. There are five major causes of elevator failure: elevator door system (37%), fixtures (16%), frequency control system (9%), shaft information (6%), and others (32%) (Phummanee 2015). Kwon et al. (2020) developed a model to predict the maintenance cost of residential buildings using the combination of Case-Based Reasoning (CBR) and a Genetic Algorithm (GA). In Kim et al. (2019), building maintenance costs have been analyzed and evaluated using the Loss-Distribution Approach (LDA) to allocate sufficient funds to maintain the building systems. Several studies have tried to determine the relationship between maintenance cost and resource allocation (in-house staffing and outsourcing) in hospitals.

Salah et al. (2018) considered elevators as mission-critical systems in hospitals. Elevator failure has a major impact on the performance of hospitals (Liu and Wu 2018; Salah et al. 2018). Liu and Wu (2018) also emphasized the importance of elevator preventive maintenance in people's daily life. Particularly, in most high-rise-building hospitals, where the issue of elevator congestion or failure causes patient dissatisfaction. Furthermore, the growing records of unexpected failures in the elevators of hospitals, and their impacts on patients' care and satisfaction have been reflected in the media. CBC NEWS has reported that breakdowns in elevators are creating crises across Canadian hospitals and highlighted the malfunctioning of the aging elevators in several hospitals in Manitoba (CBC News, 2016 a,b).

In summary, the literature points to several factors that affect the cost of maintenance in hospital buildings. Several studies have tried to capture the relationship between cost, the composition of in-house and outsourced personnel, and the maintenance contract. However, further research would be needed to develop indicators and benchmarks to assist hospitals in establishing the cost of maintenance and in shaping the maintenance (sourcing) contracts accordingly.

2.2.3 Maintenance Workflow and Resource Allocation

Cotts et al. (2010) and Roper and Payant (2014), stipulated that annually, more than 50,000 maintenance requests are made to the facility manager of a medium-sized building. Conventionally, the information of maintenance requests includes the work number, location, work type, failure code, description of the work order, reported date, and finished dates are recorded in excel sheets, to preserve historical data. However, information related to workflow and resource allocation is fragmented and inconsistent. This fragmented information poses significant challenges for hospital facility managers (Lucas et al. 2013b). Moreover, the judgment about the performance, awareness of the critical situation, and decision making are not accurate with fragmented information.

In recent years, facility managers are under increasing pressure to prioritize their ever declining resources for maintenance and replacements (Lavy et al. 2014a). Shohet and Nobili (2016) stated that the highest maintenance costs are due to the inefficiency of maintenance resource allocation and went further to show (using a survey involving more than 700 different hospitals) that almost half of the Annual Maintenance Expenditure (AME) was spent on maintenance human resource. Some of the commonly reported consequences of failing to establish such a prioritization might include unscheduled required maintenance, additional expenses, reworks in repair and replacement activities, and increasing stock of aged components. Yousefli et al. (2020) stated that arranging orders in maintenance queues and distributing resources with a huge amount of orders is one of the most important challenges that facility managers face in the maintenance management of hospitals.

Resource allocation endeavor aims to ensure timely distribution of required resources, satisfying cost, and time constraints (Nongaillard 2013). Resource allocation tasks are typically affected by the method used. Workflow management and resource allocation planning are two maintenance management functions traditionally treated separately (Lim et al. 2013).

The literature points to the fact that the O&M staffing and its sourcing have a significant influence on maintenance cost (Sliteen et al. 2011). Therefore, the sourcing of maintenance services in hospitals (outsourced vs in-house maintenance) and the structure and type of maintenance contracts are of particular importance. Ikediashi and Ogunlana (2015) have surveyed 74 hospitals to investigate their experience with outsourcing of FM tasks. Outsourcing and insourcing of maintenance activities have their advantages and issues. Outsourcing relies on external expertise, and thus, the internal skills and experience will be ignored (and lost in the long term). Also, some of the insource management and control authorities and responsibilities will be compromised via outsourcing contract and will be delegated to the external expertise. On the other hand, outsourcing has some merits, including the cost-efficiency gains, access to external state-of the-art expertise and resources and a reduced workload for the internal team so that they can focus more on monitoring and ensuring the quality of outsourced maintenance services (Shohet and Perelstein 2004). A survey of more than 700 hospitals illustrated the fact that almost half of the AME were spent on maintenance staff and over a third of that were devoted to external contractors (Shohet and Lavy 2017). This highlights the most common arrangement of outsourced and in-house staffing in hospitals.

Ikediashi and Ogunlana (2015) proposed a model for the outsourcing decision-making linking strategic decisions, economic factors and human resources. This model analyzed internal and external benchmarks as related to determination of outsourcing work requirements, selection of service provider and contract management. They suggested a model to manage the outsourcing of services in FM for a general hospital. He asserted that all of the FM practices in hospitals could be outsourced. Shohet (2010) advocated that the success of a maintenance outsourcing practice depends on the level of hospital occupancy. In hospitals with a high rate of occupancy, facilities are subject to a higher rate of deterioration requiring available in-house work sources to do CM. Otherwise, with lower rates of occupancy, outsourcing could create more cost-efficiency gains by delegating non-core FM activities to the external workforce (Shohet 2004). Mohammad Mosadeghrad (2014) mentioned that there is a positive correlation between (in-house) employees' satisfaction and hospitals' maintenance commitment. Ciarapica et al. (2008) showed that for small hospitals, employing outsourced personal is more costly than internal ones, while for large hospitals, outsourcing services are more cost-efficient, as the risks arising from complexities of large hospitals are outsourced. They suggested that there are research gaps on how the selection of the contractors needs to be carried out and how the work should be divided between in-house and outsourced personnel when both groups are on site.

Ali and Mohamad Nasbi Bin Wan Mohamad (2009) have discussed the contractor's service performance as a major issue in maintenance outsourcing contracts. They have indicated that the performance monitoring and control of external contractors have not yet been formalized in many hospitals. Straub and Van Mossel (2007) suggested a performance-based contract mechanism used to select an outsourcing contractor (among alternative contractors). To be selected, a contractor must propose their choice of maintenance strategies considering the future scenarios of the hospital in terms of services and requirements as well as the user satisfaction issues related to maintenance activities. In addition, a recent study indicated that performance-based maintenance contracts are approximately 20 per cent less costly in comparison with perspective-based contracts and recommended this type of contract as a basis for performance assessment of maintenance activities carried out by external contractors (Straub 2009).

Alzaben et al. (2014) proposed a Current Reality Tree (CRT) to identify the main issues affecting and causing delays in maintenance works in hospitals. They proposed "lack of skills", "insufficient communications", "low team motivation", "limited budget" and "low standard of contract work" as the major causes of the deferment in maintenance practices in hospital buildings. Shohet and Nobili (2016) mentioned that there is a gap between the financial resources available for maintenance in hospitals and the maintenance management expectations and requirements.

Sharma et al. (2007) applied "lean" principles to identify and eliminate non-value-added activities in facilities management of a hospital in Germany. They used simulation to illustrate and verify the impact of suggested changes on workflow process. To identify an optimal allocation of resources (such as minimizing the number of workers in an FM team), a number of "what-if" scenarios were analyzed through the means of simulation. By implementing "lean" principles, a fewer number of reworks and rejections was expected with 30 to 50 per cent decrease in activity completion times.

2.2.4 Maintenance Risk

Risk management has long been recognized as one of the high priorities for hospitals (Alzaben 2015). One of the common duties of facilities managers of hospitals is to identify and analyze the risks (internal or external) that could threaten the functioning, security and safety of the hospital facilities. In this sense, there are two categories of risks, the ones that could impact the functioning of maintenance management units in hospitals, and the ones that could originate from maintenance activities and affect other functions of hospitals.

A typical risk management process consists of risk identification, risk assessment and risk prioritization (Yousefli et al. 2017). In the risk assessment, the focus is on evaluating the criticality of risks by incorporating their likelihood and impact. In the risk prioritization, the aim is to ensure that the critical risks are addressed first and the others are carried out based on the order of their criticality. Decision trees, sensitivity analysis, scenario analysis, fuzzy, simulation and multi-attribute utility theory have been used to analyze the likelihood, consequence and criticality of risk (Okoroh et al. 2002).

Hospital risks are related to clinical, service quality and financial dimensions. Kimbrough et al. (2020) recommended a management plan for risks related to security, fire, inspection incidents, COSHH (control of substances that are hazardous to health), complaints, protective clothing, waste, workplace incidents, equipment, IT system and aggression and violence. A risk strategy was outlined to ensure that all of these items were considered in risk management through identifying risks, quantifying their likelihood and impact, identifying options to mitigate these risks, implementing the above-chosen options and assessing the period needed to execute them.

Mahfoud et al. (2016) organized a list of health and safety hazards in hospitals, including hazardous substances, manual handling of them, security, violence and aggression, fire protection, food hygiene, infection and exposure to clinical waste. He discussed three possible levels of the risk. The major risks which have serious outcome and must be mitigated, small risks that should be reduced and the tolerable ones under “no further action is required” label.

NHS hospitals in the UK face a variety of risks and uncertainty on the part of service contractors and purchases. This includes equipment and spare parts needed for in-house maintenance as well as the outsourced maintenance contracts. Okoroh et al. (2002) noted that to improve service quality and avoid clinical failures, NHS has to conduct a comprehensive review about risks and uncertainties faced by hospitals, including the ones that facility managers of hospitals should identify and analyze. They developed a risk classification framework and identified the major risk factors associated with facilities management in NHS hospitals. These risk factors are customer care risks, business transfer risks, legal risks, facility-transmitted risks, corporate risks, commercial risks and financial and economic risks, where most of these risks cannot be controlled by the FM unit.

Lavy et al. (2014b) considered five levels of risks of highly critical, critical, marginal, low and negligible for the ten typical building components including structure, exterior envelope, interior finishes, electricity, sanitary systems, elevators, fire protection, communication and low-voltage, medical gases using data collected from a series of surveys conducted at a number of hospital buildings.

De Silva et al. (2012) identified ten risk factors of building maintainability and their impact on maintenance costs. They studied these factors in a case study high-rise building. The results illustrate the fact that accounting for risks (and minimizing them) in maintenance decisions will reduce the cost of maintenance.

Ikediashi and Ogunlana (2015) considered 35 risk factors related to the outsourcing of FM services in Nigeria's public hospitals. At the end, 24 of these factors were considered as "critical". They identified the top five critical factors as inexperience and lack of requisite skills, the possibility of fraud by the vendor, financial failure of chosen vendor, vendor opportunism and fall in the morale of employees. As a result, they further categorized the above-identified risks into five distinct groups of client risks, contract risks, vendor risks, political risks and general risks. They have suggested an approach to risk management in FM operations. Their model includes four stages: risk identification, risk analysis, risk control and financing of risk consequences and loss. They advocate that risk management activities in hospitals should be prioritized based on the consequences of identified risks on cost, service quality and quantity.

Leung et al. (2014) studied the key components of FM in C&A homes using a large scale survey. They categorized FM into three main aspects: architectural, building services and supporting facilities component. Lim et al. (2013) identified the main components of FM in residential Care and Attention (C&A) homes and investigated the risks related to these components. In this context, they defined FM as the coordination of physical environment for the elderly in C&A homes to live in a non-risky environment. The common risks that could occur in C&A homes include falling, collision, scalding, infection, getting lost, behavioral disorder, fire, and security. In such an environment, the main FM responsibilities will include space planning, lighting, fixtures and finishes, ventilations, noise reduction, thermal comfort, signage, cleanliness, safety and security and leisure and catering. They developed an operational model for FM to address the risks mentioned above and to support the health and well-being of the elderly in C&A homes.

In summary, there is still very limited (mostly generic) research on identifying, evaluating, and managing facility risks in hospital buildings. The literature is even more limited in the case of analysis and management of risks associated with maintenance function in hospitals. In today's complex hospital buildings, it should not only consider the risks associated with extreme events and their consequences on maintenance functions but also incorporate risks that could arise from maintenance activities jeopardizing the continuity and quality of care services in hospitals (Lavy et al. 2014a; Roper and Payant 2014).

2.2.5 Maintenance Performance Measurement

May and Pinder (2008) provided a methodology to measure the relationship between the performance of soft FM services and the well-being of patients at NHS facilities. They did not, however, consider the impact of building maintenance, which was categorized as "hard" FM. This was considered in a follow-up study in which the perception of maintenance teams about their performance and its impact on patients' satisfaction was investigated (May and Clark 2009).

Kumar et al. (2013) identified techniques to formulate performance indicators for Maintenance Performance Measurement (MPM). Their research illustrated the value and applicability of MPM frameworks for the organization. MPM is defined as the process of measuring the value created by maintenance expenditures and investments (Parida and Kumar 2006). Meng and Minogue (2011) compared different performance measurement models in FM. These models include Balanced Score Card (BSC), Business Excellence Model (BEM), KPIs and capability maturity model. Among them, KPIs could be defined for activities at the operational level with a focus on maintenance to compare its targets and actual outcomes (Chan and Chan 2004). In recent years, research is emerging in adopting the KPI approach for FM in hospitals.

Alzaben (2015) developed a performance assessment model for FM functions in hospitals. They identified several factors affecting the performance of hospital buildings. Based on these factors, they developed a number of KPIs linking the performance of facilities with revenue of the hospital. As such, their approach would be more appealing to private hospitals because of its focus on revenue. Shohet (2006) developed a set of KPIs for strategic maintenance management for a case study hospital. The aim was to use these KPIs as a basis for selection, monitoring and control of the hospital's maintenance service suppliers.

Integrated performance-based maintenance management is a method developed to integrate indicators related to the performance and the efficiency of maintenance in hospital buildings (Shohet 2006). These indicators are Building Performance Indicator (BPI), manpower sources diagram, Maintenance Cost Efficiency Indicator (MEI) and an organizational indicator of the maintenance unit (Shohet 2010). Shohet and Lavy (2004) also developed an integrated healthcare FM model as a decision aid model to assist facility managers in their tactical and strategic decision-making. It consists of five modules of maintenance management, performance and risk management, energy and operations, business management and renovation and development. However, only the first two modules were further investigated and integrated to establish a performance measurement framework for FM functions. Lavy and Shohet (2007) asserted that their evaluation can be enhanced by incorporating additional modules.

Similarly, Enshassi and El Shorafa (2015) suggested four KPIs for maintenance activities of public hospital buildings in the Gaza Strip. These KPIs are BPI, Maintenance Cost Efficiency Indicator MEI, AME and urgent repair indicator. The latter is an indicator which shows to what extent the maintenance staffs are engaged in urgent repairs. It is the ratio of urgent repairs by guest and in-house staff to the total number of repairs (Enshassi and El Shorafa 2015). Enshassi and El Shorafa (2015) calculated BPI based on an area-based weighting method instead of the more common life-cycle costing approach as a result of lack of data on maintenance costs.

Ali and Mohamad Nasbi Bin Wan Mohamad (2009) investigated maintenance management and its performance in a public hospital in Malaysia. They defined these KPIs to assess the performance of the hospital in terms of leadership; policies, plans and procedures; training and orientation; and service performance. Their findings point to some weaknesses related to maintenance performance in hospitals, such as lack of policies, plans and procedures to trigger improvement of maintenance performance and also a lack of proper training and orientation for maintenance personnel. They also highlighted the mismatch between contractual requirements and organizational capabilities of maintenance management in hospitals. Liyanage and Egbu (2008) proposed a performance management framework for FM activities is hospitals. They used a set of KPIs to generate performance monitoring and control indicators.

There is a building performance assessment toolkit developed by the United Kingdom National Health Service (UK NHS) according to Building Research Establishment Environmental Assessment Method (BREEAM) called Achieving Excellence Design Evaluation Toolkit (AEDET). This toolkit assists evaluating the design of healthcare facilities and buildings to ensure their operational performance. In Australia, Talib et al. (2013) developed a framework for measuring the performance of healthcare buildings. They considered function, societal and environmental impacts and service quality as the performance criteria for healthcare buildings, with the maintenance unit as one of the very few components of the hospital that has direct influence on all of these criteria.

Alzaben et al. (2014) conducted a study in Riyadh Military Hospital and identified a set of Critical Success Factors (CSFs) for hospital maintenance management systems. They have investigated and reviewed total preventive maintenance, RCM and reliability-centered failure analysis and their benefits and performance implications as three maintenance management strategies for healthcare FM (Alzaben et al. 2014).

Shohet (2010) point to the fact that individual KPIs could not provide a complete diagnosis of maintenance performance in hospitals. They argue that KPIs must be selected and used according to hospitals' maintenance priorities and by taking into account the criticality and complexity of these activities. In addition, selecting an appropriate set of KPIs is influenced by issues beyond the characteristics of a hospital building and extends to supply chain factors as well as environmental, social and economic conditions and requirements (Ivanov 2017).

Enshassi and El Shorafa (2015) highlight the lack of systematic documentation and scheduling of maintenance activities as the main difficulty in establishing a performance valuation in hospitals. Talib et al. (2013) emphasize that the lack of a strategic view in maintenance management of hospitals results in undervaluing and neglecting the importance of developing useful and practical performance indicators with respect to quality, impact and efficiency of maintenance activities.

In Shohet and Lavy (2017), a study of the performance and maintenance of different hospitals shows that improving maintenance management has a great impact on the healthcare facility services. Gómez-Chaparro et al. (2018) proposed a set of KPIs to calculate the average maintenance cost and time in hospitals with less than 200 beds. Shohet and Nobili (2016) implemented KPIs in a large number of health centers to improve facility maintenance performance.

Gómez-Chaparro et al. (2018) considered variables such as the number of surgeries, the number of hospital beds, the useful floor area of the building and the number of workers, to measure the amount of medical gas consumption and the size of their facilities, to optimize maintenance management in hospital buildings.

Van Horenbeek and Pintelon (2014) provided a framework for developing KPIs for maintenance management using the Analytic Hierarchy Process (AHP). Decomposing the maintenance management issues into a hierarchy of tactical and operational sub-issues and causes using AHP provides a ranking for the root causes of performance and maintenance problems, which assist in prioritizing maintenance strategies and activities.

Li et al. (2020) developed an evaluation tool to measure the performance of hospitals, considering various dimensions, including cost-effectiveness, customer satisfaction, energy and resource efficiency, management efficiency, and operation and maintenance efficiency. They used the Delphi method and AHP to verify the effectiveness of the benchmarking model in Shanghai Municipal Hospitals. Chen et al. (2018) developed a decision-making framework to assist facility managers to address the deficiencies of traditional lighting maintenance methods and optimize maintenance alternative for the lighting system. For this purpose, they used analytic AHP and simulation methods. Liberatore and Nydick (2008) reviewed the use of AHP as a decision-making tool in healthcare facilities management. The rationale behind their choice is that in healthcare facilities management, and in particular in maintenance activities, several objectives are addressed such as cost, time, resources efficiency, etc. Therefore, Multi-Criteria Decision Making (MCDM) models such as AHP could assist in the decision-making process. In this sense, Lee and Kwak (2011) proposed an integrated approach combining Goal Programming (GP) and AHP for establishing an optimal ERP system in healthcare facilities. They addressed strategic goals of quality, cost, flexibility and delivery of healthcare services while choosing the plans that meet the hospital's mission expressed via several criteria.

Those are expressed as financial requirements, manpower requirements, revenue requirements, capacity requirements and admission requirements. It is shown that adopting such an integrated approach could enhance the satisfaction of patients and other stakeholders.

A review of the above literature concludes that the use of a set of KPIs helps to measure performance and improve maintenance management conditions in hospitals. Based on the above literature, it could be concluded that there are still gaps and shortcomings when it comes to MPM in healthcare facilities. Shohet (2010) mentioned the difficulty of establishing KPIs for complex buildings, such as hospitals, owing to the multitude and extreme variations in the scale of maintenance performance parameters.

Moreover, maintenance performance assessment needs to account for a combination of qualitative and quantitative parameters, some of which are readily measurable, such as the number of patients served, and some are difficult to monitor, such as patient satisfaction. Also, the multitude of KPIs that exist in the literature requires a proper approach to select the most appropriate ones for any particular hospital (Lavy and Shohet 2007b).

In summary, several studies have advocated the development and use of performance indicators as a means of improving the conditions of maintenance management in healthcare facilities. Despite such a consensus, there are variations and disagreements on which indicators could well represent the performance of maintenance activities, as their impacts and requirements extend into services of hospitals (which are varied in different hospitals) and are influenced by the wider social and economic factors.

2.3 Applications of IT and DSS in Management of Maintenance Information

The handling of such huge information is further aggravated by the multidisciplinary nature of maintenance decisions and by changes over the service life of healthcare facilities. This requires the transfer of information from earlier phases of planning and design to later stages of O&M (Becerik-Gerber et al. 2012). Handling and exchanging information during the maintenance management process would not be possible without IT and DSS. In this sense, many of the reviewed articles are dealing with the use of IT and DSS in implementing, facilitating and improving the maintenance management in hospitals. IT plays an important role in facilitating the exchange of information during the maintenance workflow process in healthcare facilities. IT can lead to better planning and efficient allocation of resources when implemented as part of the ERP systems in hospitals (Van Merode et al. 2004). Shohet and Nobili (2016) implemented ERP systems in hospitals and improved the performance of clinic facilities. However, the multidisciplinary nature of maintenance decisions and changes in the service life of healthcare facilities make handling information difficult. Regardless, implementing, facilitating, and improving maintenance management in hospitals could not be possible without IT and decision support systems (Lavy and Shohet 2007b; Tuli et al. 2011)

Ma et al. (2020) proposed a data-driven approach to improve decision-making on equipment maintenance by integrating RCM, Building Information Modeling (BIM), and Geographic Information System (GIS). There is a noticeable inattention towards the interconnectivity of the information required to support relevant FM activities (Yousefli et al. 2020).

2.3.1 FM Information Systems

In maintenance management of hospital buildings, facility managers are exposed to an extensive amount of information related to buildings, operations, technologies, human resources, and patients. FM challenges such as controlling cost, keeping records, and saving energy could be addressed by adopting IT in maintenance management. Meng (2015) revealed that cost savings, enhanced communication, higher productivity, and increased health and safety are some benefits of FM information systems.

Some of the above-mentioned issues could be addressed by FM information systems, such as Computer Maintenance Management System (CMMS) (Wienker et al. 2016), Electronic Document Management System (EDMS) (Katani 2014), Enterprise Asset Management System (EAM), Energy Management System (EMS) (Amaral et al. 2013), and Building Automation System (BAS) (Wong et al. 2005), Enterprise Resource Planning (ERP) System (Van Tan et al. 2009). Even though various studies have improved facility management systems in order to achieve an effective maintenance management system but these information systems individually support facility manager activities and the data is segmented between these different systems. In reality, these systems are not integrated and their data are fragmented and thus not easily transmissible between systems. This includes data related to maintenance order caused by unforeseen failures, building component database, schedule, and available resources simultaneously. Moreover, these systems do not integrate the maintenance resource allocation process with maintenance workflow management. They conventionally consider these functions separately. Additionally, the data entrance to the systems is manual, which is inefficient and time consuming (Becerik-Gerber et al. 2012; Gallaher et al. 2004; Goedert et al. 2008).

Thus, there is an incomplete set of information at any point of time that creates uncertainties and difficulties for maintenance decision-making (Goedert et al. 2008). Among the different systems, CMMS is more practical in facilitating the decision-making process by facility managers (Fouad et al. 2012). CMMS records information in a database to facilitate maintenance operations. However, its limitations include the lack of consideration of data integrity and the impact of changes in schedule and resource plan, lack of 2D/3D visualization, lack of estimating and prediction platform, and the inability to completely cover the required information at any point in time (Becerik-Gerber et al. 2012; Bortolini and Forcada 2020; Irizarry et al. 2014; Lucas et al. 2013a; Mohammadpour et al. 2016).

To address some of these limitations, using BIM has been proposed. Akhoundan et al. (2018) established a BIM program to increase efficiency in maintenance management. This program provides the required information to inspect the existing pump system of Imam Khomeini Hospital in Tehran. Bortoluzzi et al. (2019) developed an automated process to reduce the time and resources required to create BIM for FM. In this regard, Sebastian (2011) implemented a BIM system in a hospital building in the Netherlands. He advocates that BIM implementation contributes to improving change management capabilities of the maintenance unit. Lucas et al. (2013a) suggested an object-oriented model for information management in healthcare facilities. This model is also a BIM-based approach that provides tracking, storing and filtering of information. Although BIM offers many benefits to FM (Becerik-Gerber et al. 2012; Shohet and Nobili 2016) there are still gaps and shortcomings in using BIM for maintenance management that need to be remedied, for example, BIM is not a simulation-optimization platform for workflow and allocation of maintenance resources. Therefore, facility manager cannon use BIM to track order status in different workflow queues and test different resource allocation scenarios to find the optimal once.

Meng (2015) advocates that integrating IT in maintenance management in hospitals has several benefits, such as cost savings, faster and easier communication, higher productivity and increased health and safety. Lucas et al. (2013a) suggested an object-oriented model as a means of information management in the healthcare facilities. This model is a BIM-based framework that could assist in tracking, storing and filtering information during the life cycle of healthcare facilities. The novelty of this model is that it integrates and links facility information with clinical information which is generally separated in hospitals. The proposed model includes process documentation, case analysis, information analysis, UML classification, test case analysis, prototype development and evaluation. One of the main benefits of this model is that it aims at minimizing the response time to failure incidents to prevent or minimize damages to critical facilities of hospitals. Irizarry et al. (2014) developed a BIM-based approach as a means of monitoring the maintenance tasks related to FM in healthcare. They integrated an augmented reality and BIM to build an ambient intelligent environment.

IT could facilitate the exchange of information between different stages, departments and parties involved in the maintenance process. As such, it could serve as a basis for informed decision-making in maintenance management of hospitals including staffing, scheduling and execution of maintenance activities.

2.3.2 Enterprise Resource Planning (ERP) Systems

Resource allocation is the distribution of resources to entities in a window of time (Nongaillard 2013). In the sense of the current business environment, ERP has been recommended as a management system to integrate flows of information, materials and monetary transactions (Lee and Kwak 2011). IT could well serve the implementation of ERP systems in hospitals, contributing to better planning and efficient allocation of resources (Van Merode et al. 2004).

In the healthcare sector, ERP systems are extended to integrate with customer relationship management, supply chain management and clinical DSS (Lee and Kwak 2011). Incorporating maintenance activities in ERP systems can also enable facility managers to monitor the functioning of the components of a hospital in real time (Rajagopal 2002; Stefanou and Revanoglou 2006). ERP systems were originally implemented in manufacturing processes. The research shows that there are key differences between requirements in manufacturing and healthcare facilities when it comes to ERP (Grimson 2001). As such, ERP needs to be customized for healthcare applications to incorporate attributes of each peculiar hospital, such as financing, manpower recruitment and circulation, space and equipment capacities, revenue management and the patients' admission and care units (Lee and Kwak 2011). In doing so, Shohet and Nobili (2016) developed an ERP model for maintenance of clinical facilities in a public hospital by integrating eight KPIs. These KPIs are expressed as Age Coefficient for facilities (ACy), Density Coefficient for patients in the clinic (DCy), BPI, AME, Normalized Annual Maintenance Expenditure (NAME), MEI, Maintenance Sources Ratio (MSR), and Maintenance Management Span of Control (MSC). MSR represents the percentage of outsourced maintenance resources from the total labor resources allocated for maintenance of the facility. MSC is the indicator that shows the effectiveness of maintenance division to achieve coherence among different parts of the organization, which is represented by the number (ratio) of employees who are directly subordinate to the maintenance manager. Through a case study, they have presented a number of cost-saving opportunities that resulted from adopting the proposed model.

In summary, the literature review revealed that implementation of ERP systems is advocated for efficient allocation of resources in hospitals' maintenance management. However, there is still limited research on the customization of ERP systems for healthcare applications. The research in this area is still very case-specific and needs industry-wide benchmarks and KPIs.

There is an increasing interest in the use of Artificial Intelligence (AI) and Information Communication and Technology (ICT) techniques in the management of healthcare facilities

(Shohet and Lavy 2004). Shohet and Lavy (2004) proposed a healthcare FM model that incorporates ICT in the FM functions of hospitals. Lavy and Shohet (2007a) developed an AI model to integrate facility service life, the level of occupancy, and maintenance expenditure as a decision aid for performance assessment of maintenance units in hospitals. Their model is divided into three interfaces: input interface, reasoning evaluator and predictor interface and an output interface. The input interface designed was based on a deductive reasoning approach, which decomposes the available information into several hierarchies from general facility information to case-specific information related to buildings, systems, and components.

Ali and Hegazy (2014) developed a tri-level performance assessment framework for healthcare facilities, which consists of hospital data structure, assessment criteria and visual all-onsite inspection. This methodology evaluates the performance of a healthcare facility based on four KPIs: condition, level of service, sustainability and risk. The study claims that the proposed approach reduces time and cost of inspections and supports capital renewal decisions by providing timely information about the facility and its assets.

In most of the above studies, the facility information system is not linked to the patient services, which makes it difficult to capture the impact of maintenance functions on core services of the hospitals. In this sense, Mohammadpour et al. (2016) proposed a facility failure analysis model linking facility failures to the healthcare delivery process in a hospital. This model helps to identify and rank the failures that have a critical impact on service delivery, which helps prioritize planned or unplanned maintenance activities. In this regard, location, availability of information, internal and external resources, required skills, the severity of failures and the level of impact on patients and staff are the important findings from such an analysis (Mohammadpour et al. 2016).

In summary, incorporating IT is one of the main challenges in managing and maintaining healthcare facilities. In addition, various areas have been identified that need further updating and research. On that basis, the remaining issues and research gaps as related to maintenance management in hospitals have been identified. Table 2-1 provides a summary of methodologies, findings and the identified gaps in the literature (Yousefli et al. 2017).

Table 2-1. Summary of literature on maintenance management in hospitals.

Authors	Methodology	Findings	Identified research gaps
Maintenance strategies			
Shohet and Lavy 2017	Literature review	Developed the Pentagon of healthcare FM	Limited research reported applying the maintenance strategies planning (Corrective and Preventive maintenance) in hospital buildings
Rani et al. 2015	Questionnaire, survey	Investigated relationship between maintenance strategy and end-user	
Diez and Lennerts 2009	Data collection from four German hospitals	Developed a model for cost allocation of FM services.	Need to further research on measuring and quantifying the effect of maintenance strategies planning in healthcare facilities.
Maintenance cost, sourcing, and contract management			
Sliteen et al. 2011	Literature review, cases of health facilities in France	Identified cost per bed ratio as an efficient metric to classify performance of healthcare facilities.	
Boussabaine et al. 2012	Data collection from hospital facilities in Paris	Demonstrated the effects of medical activities on the operation and maintenance cost of hospital.	Inappropriate framework to optimize the maintenance cost through bidding mechanism for outsourcing maintenance service
Assaf et al. 2011	Questionnaire survey, literature review, cases in the Saudi Arabia	Identified the factors influencing the decision to outsource maintenance services.	
Shohet 2003	Literature survey, statistical analysis of data	Examined performance versus maintenance expenditures, Developed additional KPIs.	Limited research to identify the relationship between cost, composition of in-house and outsourced personnel, and contract
Franceschini et al. 2003	Benchmarking, simulation	Developed a simulation model to analyze outsourcing decisions.	
Shohet 2010	Surveys, KPIs	Developed an evaluation methodology for the building's condition before and after maintenance or rehabilitation.	

Ciarapica et al. 2008	Interviews	Identified the relevant variables for the outsourcing decision-making process in hospitals.	
Ikediashi and Ogunlana 2015	Questionnaire survey	Surveyed hospitals to investigate their experience with outsourced FM	
Ali and Mohamad Nasbi Bin Wan Mohamad 2009	Case study, questionnaires, interviews	Identified contractor's service performance as a major issue in maintenance outsourcing contracts.	
Straub and Van Mossel 2007	Literature review, interviews	Developed a performance-based contract mechanism to select an outsourcing contractor.	
Alzaben et al. 2014	Data collection, Current Reality Tree (CRT) and Thinking Process (TP), Theory of Constraints (TOC)	Identified the critical success factors (CSFs) in maintenance management.	
Shohet and Nobili 2016	Literature review, questionnaire, inference engine, inferential statistical analysis	Developed a performance-based model by integrating KPIs into an enterprise resource planning (ERP) system for the maintenance of public clinic facilities.	
Maintenance resource allocation			
Lee and Kwak 2011	Multi-criteria decision-making (MCDM), Goal programming(GP), Analytical hierarchy process	Developed an integrated multi-criteria decision-making model to implement ERP for healthcare planning.	Lack of resource allocation framework to integrate maintenance process planning with maintenance scheduling Lack of framework to optimize maintenance resource management process subject to minimum
Rajagopal 2002	Case study	Investigated the implementation of ERP systems in healthcare sector	

Sharma et al. 2007	Lean Principles, Simulation, Data collection, case study of hospitals in Germany	Provided an optimization and simulation resource allocation framework.	"extracted time" of failed building component Lack of study to customize ERP systems for health care applications Few available approaches developed to optimize resource allocation and planning for maintenance management in hospital facilities
Lennerts et al. 2005	Data collection, Linear regression, data analysis, case study of a hospital in Germany	Provided a model to seek optimization of FM processes through cost allocation and efficiency of performance.	
Maintenance risk management			
Alzaben 2015	Case study	Emphasized the necessity of the risk management in hospitals. Investigated the FM related risks in healthcare sector.	Limited literature on identification, evaluation, and management of risks associated with maintenance functions in hospitals Very limited research on reliability analysis of hospital facilities Need to more research on identifying and quantifying the vulnerabilities of maintenance functions in hospitals
Okoroh et al. 2002	Literature review, meetings and interviews with facility managers of hospitals, case study Collecting information using a facilities management information system	Identified and classified the FM risk factors in National Health Service hospitals. Prioritized the risk management activities in hospitals considering cost, service quality, and quantity.	
Lavy, S. and Shohet 2010	Case study	Developed an integrated performance-based facility management for hospitals.	
De Silva et al. 2012	Survey	Identified the risk factors associated with maintenance of high-rise buildings.	
Ikediashi and Ogunlana 2015	Questionnaire survey, case study, interview	Ranked the risk factors in FM outsourcing.	
Leung et al. 2013	Questionnaires, Pearson correlation, and partial	Identified risk profile of FM components	

	correlation analyses, a case study of care and attention homes		
Maintenance performance measurement			
Parida and Kumar 2006	Multiple criteria analysis	Identified the issues and challenges associated with MPM.	Absence of industry-wide benchmarks and KPIs for measuring the resource performance in hospital buildings Limited research on understanding the operational issues in establishing KPIs for maintenance in complex hospitals Very limited research on implementation of the KPIs Limited research on the measurement of performance for outsourced services in hospitals.
Meng and Minogue 2011	Literature review, expert interview and questionnaire survey	Compared performance measurement: using the Key performance indicators (KPI), the Balanced Scorecard (BSC), and the Business Excellence Model.	
Chan and Chan 2004	Literature review, case study, KPIs	Developed the methodology for measuring project performance for construction project.	
Shohet 2010	Field surveys, statistical analyses, case studies	Developed a set of KPIs for monitoring the performance, maintenance, and cost effectiveness of hospital facilities.	
Van Horenbeek and Pintelon 2014	Application of ANP methodology	Developed a decision support for implementation of a customized MPM system.	
Liyanage and Egbu 2008	Case study, data collection, statistical analysis	Developed a performance analysis framework for case study hospitals using KPIs	
Shohet and Lavy 2017	Surveys, KPIs	Developed a methodology to evaluate the building's condition during maintenance or rehabilitation.	
Shohet and Nobili 2016	Literature survey, statistical analysis of data	Compared performance versus maintenance expenditure of hospitals, developed additional KPIs.	
Shohet and Nobili 2016	Survey among acute care facilities in Israel; statistical analysis of the data	Developed an integrated model for healthcare FM.	

Enshassi and El Shorafa 2015	Case study of Gaza public hospital buildings	Investigated KPIs for performance and expenditures assessment.	
Ali and Mohamad Nasbi Bin Wan Mohamad 2009	Case study of a public hospital in Malaysia, Questionnaire and statistical analysis	Identified weaknesses related to maintenance performance. Investigated the maintenance team perception about their performance and its impact on patients' satisfaction and well-being	
Talib et al. 2013	Case study of a public hospital in Australia, questionnaire, survey, statistical analysis	Develop a framework for measuring performance.	
Lavy et al. 2014b	Simulation	Developed a simulation tool for decision-making in maintenance and replacement of building systems	
Fard et al. 2016	Discrete-event simulation, Data collection from a case hospital	Developed a discrete event simulation model for patient flow, resource allocation, and performance monitoring of emergency departments.	
Information technology and decision-making			
Ali and Hegazy 2014	Data collection, survey, multiple criteria analysis	Developed a performance assessment framework for healthcare facilities	Limited research has been conducted to develop and implement decision support systems crafted to specific needs of maintenance management units in hospitals The absence of maintenance functions and issues from most reported management information systems developed for hospitals.
Chotipanich and Sarich 2004	Literature review	Proposed a decision-making framework for improving FM position in hospitals	
Lucas et al. 2013a	Case study, BIM	Developed an object-oriented model to integrate facility information with clinical information	
Becerik-Gerber et al. 2012	Data collection via interviews, expert	Identified potential application areas, benefits, and barriers of implementing BIM in FM	

	interviews, online survey		Fragmented and in complemented information system of healthcare facility management
Meng 2015	Criteria analysis, decision mapping, and decision support, Semi-structured interview	Developed a maintenance program to link preventive maintenance and emergency maintenance.	
Sebastian 2011	Desk research	Overviewed the issues related to implementation of BIM in hospital buildings.	
Lavy and Shohet 2007a	Decision support system	Developed a decision support system for healthcare facility management	
Liberatore and Nydick 2008	Literature review	A review of applications of AHP to health care FM	
Mohammadpour et al. 2016	Case-study, scenario analysis	Investigated the interactions between facility failures and the healthcare delivery process	
Irizarry et al. 2014	Mobile augmented reality (MAR) and building information modeling (BIM)	Developed a BIM-based approach to improve performance of facility mangers in maintenance tasks, Provided a communication environment for geographically distributed stakeholders to provide input for FM activities.	

2.3.3 Resource Allocation Systems

According to Nongaillard (2013), the centralized and distributed systems are the two main resource allocation systems reported in the literature. It is pertinent to mention that maintenance management systems are centralized in most hospitals. A centralized system is typically following three steps, to solve the resource allocation problems: “information gathering”, “computations”, and the “notification of the outcome to all resources” (Nongaillard 2013). However, centralized systems are not efficient in solving resource allocation problems, since the solution space grows exponentially by an increase in the number of activities and resources (Nongaillard 2013). Indeed, in dynamic applications, centralized approaches become far-fetched, because they cannot consider new data evolution. In order to handle the evolution of initial data, centralized systems have to fully restart the problem-solving process.

Distributed systems overcome the limitations of centralized systems (Baškarada et al. 2020; Singh et al. 2014). Multi-agent system (MAS) is a distributed computational method that consists of several intelligent agents that interact with each other in an environment (Li et al. 2016). In MAS, agents actively participate to fulfill the objective of the system. The inclusion of agent negotiations makes agent-based systems more practical and efficient, with the ability to handle the allocation problem of large dynamic systems. Local negotiations among agents improve the optimization process gradually. Agents' decisions to achieve the optimal solution are influenced by MAS communications. Distributed systems architecture consists of independent computers that are connected over a network as a single integrated system (Singh et al. 2014). Storing data across multiple databases makes distributed systems more reliable as it reduces the likelihood of data loss in crash conditions compared to centralized systems.

In summary, there are two resource allocation systems; centralized and distributed systems. In a dynamic environment such as hospitals, centralized systems cannot consider new data evolution. In this situation, any failed building component initiates new data and requirements for maintenance. In a centralized system, this new arrival of resource needs requires new resource allocation solutions, and thus, creates delays in maintenance. In such cases, distributed (agent-based) systems can overcome the limitations of centralized systems. Therefore, it is necessary to develop a distributed system to address the dynamic nature of the maintenance environment in hospitals.

2.3.4 Centralized and Distributed Systems' Architectures

The system architecture illustrates how different elements are arranged to form the system and how these elements interact with each other. Dragoni et al. (2017) investigated practical issues and potential solutions in the field of software architecture. A centralized system has a central server node, which is directly connected to client nodes through communication links. Centralized systems are generally designed in client-server architecture and monolithic architecture (Yan et al. 2013). Grgić et al. (2016) proposed restructuring of monolithic architecture into a three layers architecture including presentation layer (user interface), business layer (logic), and data access layer. Salah et al. (2017) compared the four types of distributed architectures, i.e., client-server paradigm, mobile agents, Service Oriented Architecture (SOA), and microservices in terms of the desired features. They concluded that microservices can deliver greater scalability, integrity, resilience, and agility than other distributed architectures. Microservices are an architectural style of developing software systems. Microservice is a set of smaller independent services, each is executed independently using its database. These services communicate with each other via an inter-service (lightweight) communication mechanism. Gabbrielli et al. (2016) stated that among different software architecture microservices are the most suitable architecture to develop distributed systems, particularly in the cloud.

Alshuqayran et al. (2016) investigated the challenges and quality attributes of the microservices architecture. Alpers et al. (2015) developed Business Process Modeling (BPM) tools using a microservices architecture. While microservices can overcome the problems associated with monolithic software architectures, there are challenges associated with the implementation of microservices (Baškarada et al. 2020; Strimbei et al. 2015). Braun et al. (2017) and Rudrabhatla (2018) implemented microservices in the Java framework Spring Boot. Component-Based Software Engineering (CBSE) is a new software development technology that has emerged to overcome the limitations of current technology. CBSE is an approach to develop software systems through the assembly of components with defined software architecture (Al-Wesabi et al. 2019).

Al-Al-Wesabi et al. (2019) proposed a distributed component-based system, which results in fewer delays and more number of processes.

Dumbrava et al. (2005) used a three-tier architecture to develop an enterprise application, which includes: (1) a presentation tier; (2) a business logic tier; and (3) a database tier. In addition, to facilitate the relationship between input, processing, and output tasks, a Model-View-Controller (MVC) was developed. It should be mentioned that MVC is within the presentation tier. Dumbrava et al. (2005) employed UML to define ERP architecture. UML is derived from the domain of computer programming to hold the concept of object-oriented thinking (Gomaa 2006). UML is an effective method and standard notation for modeling a system in a programming environment. UML consists of structural and behavioral diagrams including use case and class diagrams, which describe the logic of the system; sequence diagram, which shows the interaction within the system; component diagram, which illustrates the functionality of the system. Sukhopluyeva and Kuznetsov (2017) used a UML to present the architecture of the corporate user support system. Use case, state, and component diagrams are employed to describe the actors of the system, functional capabilities of the system, and major components of the system respectively. Abu-Taleb and Mustafa (2010) proposed a Single Sign-on (SSO) model for remote portlets requests. SSO is a user authentication service that allows the user to log in securely with a valid set of usernames and passwords. There is only one entry to access the system by applying SSO.

2.4 Simulation Methods for Maintenance Management

Maintenance resource allocation is a highly unstructured decision-making problem, where facility managers have many factors to consider. These factors include prioritizing the requested orders, arranging orders in different queues, and making resource allocation decisions within the constraints of limited time, resources, and budget limits. Thus, maintenance resource allocation is a complex process, encompassing multiple resources that have varying responsibilities, behaviors, and interactions. Liu and Mohamed (2008) revealed that few research efforts have managed to address the management of maintenance functions in line with the dynamic nature of FM tasks in hospitals. The problem of providing the schedule to support the resource allocation plan with consideration of the unforeseen events can become complex while realizing the optimal solution. This dynamism is a big challenge for problem-solving using mathematical approaches (Zhou et al.

2004). The mathematical model postpones the computation of unexpected events and creates unexpected delays. So, the failed system or building component should wait for maintenance, which can lead to financial losses and dissatisfaction of patients. Simulation models are invaluable tools to solve complex and dynamic problems. Simulation is a useful tool to generate and investigate different future scenarios for a system (such as a hospital) according to past trends, current conditions as well as expectations about the future performance of hospitals and their maintenance functions (Lavy et al. 2014b). Simulation not only facilitates long-term decision-making and planning but also provides insights into understanding the impact of such decisions and plans. In the case of maintenance performance in hospitals, simulation approaches were mostly developed to quantify the future trends of KPIs (Lavy et al. 2014a). In particular, simulation is used to analyze maintenance expenditures in the long term, and to ensure that they are below a target, referred to as Condition Index (CI), while providing quality services according to requirements and expectations (Dessouky and Bayer 2002; Lavy et al. 2014b; Montazer et al. 2003).

2.4.1 Simulation Methods

Simulation methods are well-known tools utilized to predict the behavior of complex and dynamic systems and solve these kinds of problems. There are several advantages of using simulation-modeling techniques as a decision support tool for maintenance resource allocation gleaned from literature (Cao et al. 2015; Nongaillard 2013; Osman 2012; Sharma et al. 2007). In this section three computer simulation methods are compared, to identify their potential capacity to simulate the maintenance management process and resource allocation plan. The comparison takes into account all the simulation methods to find the best approach to simulate the dynamic environment of maintenance resource allocation of hospitals. System Dynamic (SD), Discrete Event System (DES), and Agent-based Model (ABM) are compared to identify their potential capacity to simulate resource allocation.

2.5.1.1 System Dynamic (SD)

SD is the most well-known type of simulation. In SD, simulation model variables change in a continuous manner. SD was first presented by Jay Forrester in a book titled “Industrial Dynamics”

(Forrester 1994). SD was introduced to solve complex problems in the industrial and manufacturing sectors. Furthermore, the overall behavior of the system is deterministic. SD generates feedback loops among the participants to show their interactions (Alzaben 2015).

2.5.1.2 Discrete Event Simulation (DES)

DES is a top-down approach and an effective tool for process simulation, as with the construction process, for example (Ben-Alon and Sacks 2017; Sharma et al. 2007; Siebers et al. 2010). The events are managed by the available resources, such as resources, material, and information. Sharma et al. (2007) implemented Lean principles to identify and eliminate non-value-added activities in the service management process flow in typical hospitals. DES was employed to monitor the impact of lean implementation on the resource allocation plan. Their research showed that simulation can be used as a powerful tool by facility managers to improve decision-making in resource allocation. Goh and Goh (2019) used DES to present Prefabricated Prefinished Volumetric Construction (PPVC) in the simulation model. They carried out a sensitivity analysis to validate their model. They changed Yield Rates and observed the output of the model in relation to these changes. The percentage of changes in the model output showed that the model output was not sensitive to changes in model parameters. So, their DES model was validated by applying sensitivity analysis. It can be concluded that DES is a reasonable method to simulate the maintenance management process. However, DES is not capable of simulating the complex behaviour of maintenance resources, which has a major impact on the outcomes of maintenance practices. This process contains five levels: registration, ascertainment, planning, execution, and documentation. They used DES to observe the impact of these changes in the resource allocation plan. Their research shows that simulation can help facility managers to make decisions regarding optimum resource allocation. Fard et al. (2016) used DES to evaluate the impact of home-hospital care in reducing emergency visits and crowding. The patients and request resources were modeled as a network of system entries. The bed-cleaning turnaround time is selected as an indicator for the performance of emergency units.

2.5.1.3 Agent-Based Modelling (ABM)

ABM is a simulation technique considered in this research to investigate its application in resource allocation and operations. ABM as a distributed system tries to solve the overall problem by facilitating the collaboration between agents and synthesizing individual agents (Barbati et al. 2012; Zhou et al. 2004). In a distributed system, the optimization process is a participatory one, with interactions and negotiations among the agents (decision-makers). ABM is a more recent method than DES. The agents respond randomly to the conditions in the environment based on a set of rules (Ben-Alon and Sacks 2017). Therefore, the objective of the system is achieved as a result of the interaction among individual agents (Borshchev 2013; Trigueiro de Sousa Junior et al. 2019).

Dignum (2017) compared the ABM and MAS in terms of methodology and application. ABM is classified as a form of computational modeling for analytical purposes. ABM models are used to capture the dynamics of social systems. ABM controls the agents to obey the assigned rules, which form the agent's behavior, even if the agents are not intelligent. MAS is an operational system, which is used to solve complex problems through the use of autonomous agents. MAS is governed by one or several interdependent ABMs. MAS is a distributed system, which is rarely employed to model dynamic applications such as resource allocation problems. In distributed systems, complex problems are decomposed into several sub-problems to be solved. So, MAS has faster computational times.

2.4.2 Comparison of Simulation Methods

In turn, an in-depth literature review was conducted to investigate current simulation methods and their applications in facility maintenance management, in general, and resource allocation and operations, in particular. As shown in Table 2-2, the simulation methods were compared with each other in order to select the most appropriate simulation technique to address the issue of the resource allocation problems.

Table 2-2. Comparison of simulation methods.

Simulation methods	Modeling Technique	Time progression	Mathematical equation	Individual properties	Adaptation to real
SD	Top-down modeling approach	Continuous	Deterministic	Does not suitable for dynamic modeling	The model is not flexible in terms of unexpected changes
DES		Discrete	Stochastic		
ABM	Bottom-up modeling approach	Combination of discrete and continuous	Stochastic (relies on the randomness of variables)	Flexibility in modeling agent's character, Each agent has its thread of control	Replicating the real-world operations by adapting and behaving differently in different situations

2.4.3 Superiority of ABM over Other Simulation Methods

Reviewing the above literature, ABM is offered to simulate maintenance resource allocation. Several reasons are highlighted to support this idea as follows. ABM has the ability of modelling and simulating dynamic and large-scale environments (Siebers et al. 2010). Furthermore, ABM is well-suited to modeling stochastic processes (Cao et al. 2015; Chevaleyre et al. 2006; Osman 2012). ABM creates combined time progression models, discrete and continuous, during the simulation (Barbati et al. 2012). To the best of the authors' knowledge, very few studies have used ABM to address the issue of maintenance resource allocation in hospitals.

2.4.4 ABMs vs. Classical Approaches

ABMs have been recently used to solve complex problems (Barbati et al. 2012; Madejski 2007). Table 2-3 summarizes the differences between ABMs and classical heuristics.

2.4.5 ABM for Maintenance Resource Allocation

Multi-Agent Resource Allocation (MARA) is a method used to solve resource allocation problems. Here, allocation means the appropriate distribution of resources among agents (Chevaleyre et al. 2006). Chevaleyre et al. (2006) developed an ABM for scheduling FM in residential buildings. They applied the MARA method and categorized agents into three types: occupants, facility manager, and problems. Osman (2012) used ABM as an FM tool to improve the satisfaction of residents in buildings. To the author's knowledge, ABM has significant potential for studying the maintenance resources' behavior, communication, and operations, in a dynamic environment. However, there is limited research applying ABM for FM.

Summary of literature related to facility information systems, resource allocation systems, system architectures, and the application of simulation methods in maintenance management is provided in Table 2-4. In addition, the findings of these papers are compared to identify gaps and limitations in these areas.

Table 2-3. Comparison of ABMs and classical approaches.

Dimension	**ABMs**	**Classical approaches**
Algorithms	Heuristic techniques	Optimization techniques
Environment	Distributed/complex/ heterogeneous (Decomposed scheme)	Centralized approach
Size of problem	Suite for large size problem by dividing problems into several sub-problems	Inadequate for large-scale
Nature of problem	Divide global problems into several local problems (modular in nature)	Centralized approaches (monolithic in nature)
React to changes	Higher reactiveness degrees	Long time to respond to changes
Computational times	Lower computational complexity	Higher computational complexity

Table 2-4. Summary of literature related to facility information systems.

Topic	Authors, year	Findings	Identified gaps and limitations
Healthcare facilities maintenance management	Yousefli et al. 2017	Organized literature and identified gaps in the field of healthcare facility management.	Very limited research has been conducted to address the issue of deferred maintenance in the health care sector.
	Gómez-Chaparro et al. 2020	Proposed indicator to measure the efficiency of maintenance in hospitals with less than 200 beds.	
	Amos et al. 2020	Developed FM performance measurement in Ghana's public hospitals.	
	Beckman 2014	Investigated the impact of Old Age Security (OAS) on federal government budget.	
	Roberts and Samuelson 2015	Investigated factors affect deferred maintenance in hospitals.	
	Alzaben et al. 2014	Identified factors affect deferred maintenance in healthcare industry (case study hospitals in Saudi Arabia).	
Facility Information Systems	Van Merode et al. 2004	Investigated potential of ERP systems for healthcare delivery organizations.	Lack of a real-time facility information system causes patient-safety problems in hospitals.
	Lavy and Shohet 2007b	Developed a decision support system to manage healthcare facilities	
	Meng 2015	Discussed the evolution and FM maturity over the past two decades.	
	Wienker et al. 2016; Fouad et al. 2012	Discussed the advantages of using a computer maintenance management system (CMMS) to improve maintenance performance.	
	Katani 2014	Studied the benefits of using an electronic document management system (EDMS) in a hospital.	
	Wong et al. 2005	Reviewed literature on intelligent building and building automation system (BAS).	
	Lucas et al. 2013a; b	Developed an object-oriented model for facility management of hospitals (BIM).	
	Irizarry et al. 2014	Developed a BIM-based model for facility management.	

	Becerik-Gerber et al. 2012	Identified benefits of BIM implementation for FM.	
	Mohammadpour et al. 2016	Studied interaction among different parties in the health care ecosystem and emphasized the need to develop real-time communication tools.	
	Bortolini and Forcada 2020	Proposed a text mining approach to improve information gathering within CMMS.	
	Sebastian 2011	Reviewed the application of BIM in hospital building projects.	
Resource Allocation Systems	Nongaillard 2013	Investigated the application of agent-based approaches for distributed resource allocations.	Limited research on addressing the complexity and dynamic nature of maintenance resource allocations.
	Singh et al. 2014	Studied the development of a new constellation of existing CMMS based on the concept of a distributed system.	
Centralized and Distributed Systems' Architectures	Dragoni et al. 2017	Reviewed the history of software architectures and explored practical issues and potential solutions.	Microservices architecture is popular among different types of software architecture. It is the most appropriate architecture for distributed systems.
	Yan et al. 2013	Proposed novel model-driven software architecture for systems based on decentralized architecture.	
	Salah et al. 2017	Studied distributed architecture systems from the traditional client-server model to the recently microservices architecture. Compared the characteristics of a microservice architecture with a monolithic architecture.	
	Gabbrielli et al. 2016	Addressed the challenges of microservices and developed a Service-Oriented Architecture configuration tool.	
	Alshuqayran et al. 2016	Investigated a systematic mapping of microservices architectures and their implementation.	
	Alpers et al. 2015	Studied microservices and developed Business Process Modeling (BPM) tools based on microservices architectures.	
	Strimbei et al. 2015	Investigated the most common types of systems architectures.	
	Baškarada et al. 2020	Discussed the opportunities and challenges associated with the implementation of microservices.	
	Braun et al. 2017	Developed two prototypes based on a microservices architecture.	
	Rudrabhatla 2018	Implemented microservices in spring boot technology.	
	Al-Wesabi et al. 2019	Proposed a distributed component-based system.	
	Dumbrava et al. 2005	Designed an enterprise application based on the three-tier architecture.	

	Gomaa 2006	Designed an object-oriented distributed system using UML.	
	Sukhopluyeva and Kuznetsov 2017	Developed a corporate user support system. Presenting its architecture in a form of the UML diagrams.	
	Abu-Taleb and Mustafa 2010	Addressed security problems in web applications by using SSO.	
Simulation Methods of Maintenance Management	Sharma et al. 2007	Provided a DES model for resource allocation framework.	Very limited research applies ABMs with a focus on maintenance resource allocation issues pertinent to hospitals
	Ben-Alon and Sacks 2017	Used ABM to simulate the behavior of crews in the construction field.	
	Osman 2012	Developed a ABM framework as a solution for FM issues, such as occupant satisfaction.	
	Chevaleyre et al. 2006	Introduced allocation of resources within a system of autonomous agents (ABM). Investigated issues related to multi-resource allocation and identified its potential application areas.	
	Cao et al. 2015	Developed an agent-based maintenance-scheduling framework to improve occupant satisfaction.	
	Zhou et al. 2004	Employed multi-agent systems for bus maintenance scheduling.	
	Barbati et al. 2012	Reviewed the application of ABM to solve optimization problems.	
	Dignum 2017	Reviewed software architectures in terms of their practical limitations and proposed several possible solutions.	

2.5 Simulation-Based Optimization (SBO) for Maintenance Management

The challenge of providing a resource allocation plan, which considers unforeseen failures while realizing the near-optimal solution, can become complex. It, therefore, becomes necessary to develop a novel system to handle the dynamic maintenance environment while also ensuring the optimum utilization of resources, subject to certain constraints, such as maintenance time in hospitals. One means by which this novel system can be facilitated is through SBO. Alrabghi and Tiwari (2013) systematically reviewed recent studies that have used SBO methods to optimize maintenance operations.

Meta-heuristic methods have become popular optimization methods for solving maintenance problems in recent years (Lynch et al. 2013). Moinian et al. (2017) used a GA to optimize the maintenance plan to reduce maintenance costs and increase availability in industrial gas turbines. Hao et al. (2010) used a meta-heuristic algorithm to solve the problem of multi-project scheduling for facility maintenance management. Farrokhi-asl et al. (2016) used two meta-heuristic algorithms to find an optimal maintenance policy to reduce total production and maintenance costs. Harmony search and simulated annealing algorithm were proposed to optimize maintenance periods. Gunal et al. (2010) reviewed SBO methods and the application of meta-heuristic algorithms in commercial software. Furthermore, they presented a real-world project that used SBO to predict performance and measure risk.

Meta-heuristics approaches have been developed to find solutions to complex problems. The meta-heuristic algorithm finds near-optimal solutions and offered a way to improve the performance of simple heuristic procedures. The meta-heuristic search algorithm uses adaptive memory to recall previous solutions and combine them with new solutions (Shahi and Pulkki 2015). As a result, a new set of solutions is generated. Gradually, this iterative process produces a very efficient path to achieve the best solutions. In addition, the meta-heuristic search algorithm does not get trapped in local solution spaces because it does not use the hill-climbing approach (Shahi and Pulkki 2015).

2.5.1 OptQuest Optimization Algorithm

OptQuest is a general-purpose optimizer using a meta-heuristic search algorithm (Al-Ahmari 2010). OptQuest automatically generates various simulation scenarios to find the best feasible outcomes with respect to certain constraints (Shahi and Pulkki 2015). OptQuest uses a combination of several optimization methods, i.e., Scatter Search (SS), Tabu Search (TS), and Neural Networks (NN) into a single search heuristic to solve optimization problems for complex systems (Ekren and Ekren 2009). SS is a population-based heuristic method for solving optimization problems (Eltawil and Elnagar 2007; Sharda and Vob 2005). SS is a local search-based meta-heuristic method for solving optimization problems. TS seeks the neighborhood of the current solution space to find a better solution in each iteration. TS records the history of recent searches in the Tabu list to prevent revisiting the previous solutions (Corman et al. 2016).

2.5.2 Coordination Between Simulation and Optimization

OptQuest can be categorized as a SBO method. The simulation model is used to calculate the objective function parameters, which can later be used as input parameters for the optimization engine. The OptQuest optimizer interacts with the simulation model with the values of the decision variables and evaluates the objective function in the simulation model (Eltawil and Elnagar 2007). OptQuest considers the simulation model as a black box (Trigueiro de Sousa Junior et al. 2019). It means that OptQuest only considers the inputs and outputs of the simulation model (Kleijnen and Wan 2007). OptQuest follows the following steps according to (Shahi and Pulkki 2015; Kleijnen and Wan 2007): 1) eliminates a candidate solution if it does not fit the constraints, 2) evaluates the simulation outputs, 3) combines these outputs with the best output of previous simulations, 4) generates a new set of decision variables values to evaluate, 5) continues the search process until termination criteria are met.

2.6 Summary

Overall, this chapter has identified available literature in the field of maintenance management for healthcare facilities. As shown in Table 2-1 and Table 2-4, the literature on maintenance management in healthcare facilities and hospital buildings has so far been very limited. In summary, the primary gaps that have been identified in relation to the objectives of this thesis are as follows:

- Very limited research has been conducted to address the issue of deferred maintenance in the health care sector.

- Lack of real-time facility information systems. In fact, FM information systems are not integrated and their data is fragmented, therefore, information is not easily transferable between systems.
- Limitations of centralized systems to consider the evolution of primary data and handle the complexity of the decision-making process in hospitals.
- Lack of consideration of the complex and dynamic nature of resource allocation in development of FM information systems in hospital maintenance management.
- Inefficient resource allocation systems have a negative impact on the communication between resources and their access to the required information.
- Lack of resource allocation framework to integrate maintenance process planning with maintenance scheduling.
- Very limited research has used agent-based simulations to solve resource allocation issues in the maintenance of hospitals.
- Lack of framework to optimize maintenance resource management process subject to minimum "down-time time" of failed building components.
- Few available approaches have been developed to optimize resource allocation and planning for maintenance management in hospital facilities.
- Very limited research has used a SBO method to optimize resource utilization in the maintenance of hospital buildings.

It can be concluded that maintenance delays are primarily due to the unstructured workflow process and the sub-optimal allocation of resources. To the best of the authors' knowledge, there has been very limited research applying distributed systems with a focus on maintenance resource allocation issues pertinent to hospitals. So, an automated and distributed maintenance management system is proposed to overcome the limitations of centralized systems. The implementation of such a system could improve the performance of maintenance activities, decrease maintenance delays, increase patients' satisfaction, and reduce the risk of failures. In the next chapter, an overview of the proposed method and three models are elaborated in detail.

CHAPTER 3. OVERVIEW OF THE DEVELOPED METHOD

3.1 Background

This research contains the development of a method consisting of three models to address the main objective of the research. These main models are entitled MAFMS, Simulation models, and SBO model, as shown in Figure 3-1. Each model consists of several phases that are designed to achieve the goals of that model. Model 1 is described in Chapter 4, while Models 2 and 3 are explained in Chapter 5.

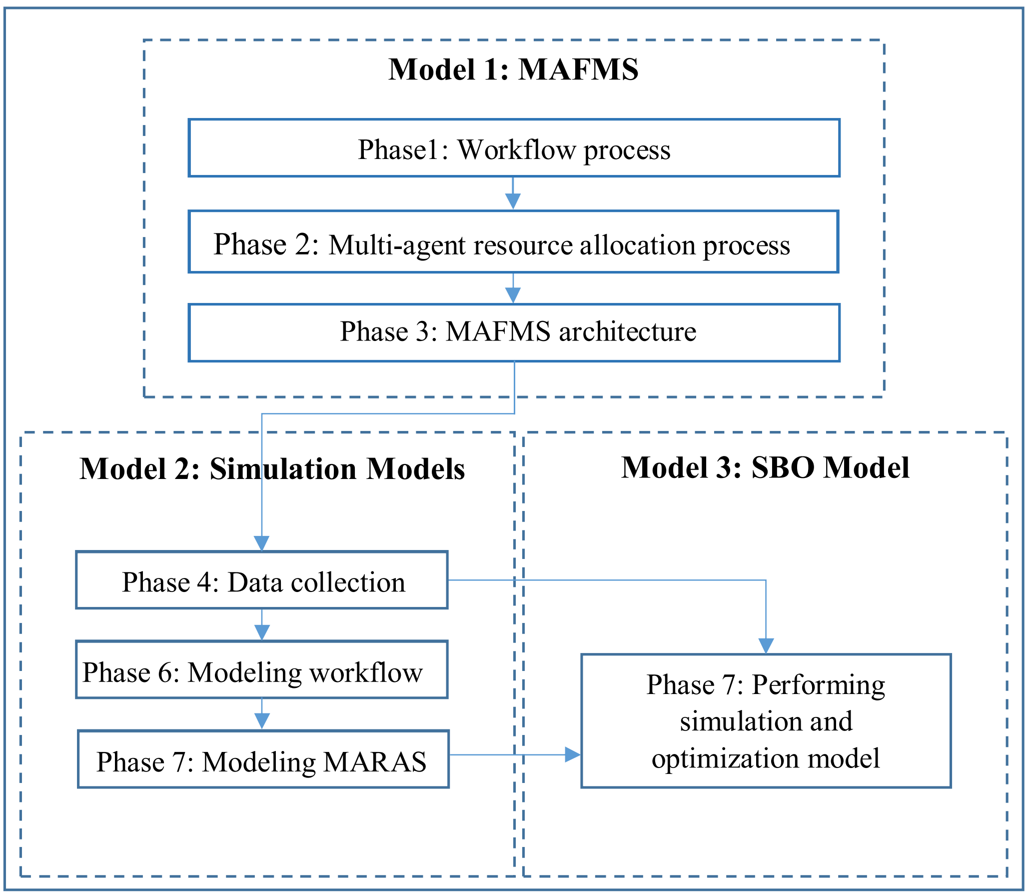


Figure 3-1. Structure of the proposed method.

3.2 Multi-Agent Facility Management System (MAFMS)

A distributed system is developed to integrate segmented information at different levels of maintenance management with the aim of minimizing maintenance delays in hospital buildings.

MAFMS aims to reduce maintenance delays by improving the maintenance workflow and resource allocation process. It should be noted that the focus of this study is only on human resources assignment to maintenance processes. These resources are represented by agents that follow certain rules and interact with others generating distinct behavior and decision making. The proposed system facilitates management of the workflow and resource allocation process and expedites updating of the maintenance schedule for improved time effectiveness.

In order to achieve the objectives of the MAFMS, three phases including: (Phase1) workflow process development (Section 3.2.1); (Phase 2) multi-agent based resource allocation model development (Section 3.2.2); and (Phase 3) MAFMS architecture development (Section 3.2.3) are designed. Model 1 is described in Chapter 4.

To develop MAFMS, in Phase 1, the maintenance workflow process is developed, which has five steps, i.e., order registration and ascertainment, order prioritization, resource allocation, execution, and supervision and documentation. Then in each step, maintenance orders are assigned to the relevant human resources. Consequently, in Phase 2, the resource allocation process is translated into an agent-based schema. Thus, agents and rules are defined as well as the interaction between agents. In Phase 3, UML diagrams are used to represent the architecture of the MAFMS. Finally, the GUI is designed so that the facility manager can enter, retrieve, and store data in the developed system.

3.2.1 Workflow Process Development

The first step in developing a MAS for maintenance management is to develop a workflow process. The proposed workflow process facilitates the arrangement of the maintenance orders in different queues. This process is presented according to the hierarchy of the workflow process in typical hospitals.

The workflow process consists of a sequence of several actions shown by activity diagrams in Section 4.2.1. In the next phase, based on this workflow process, maintenance orders are assigned to the relevant resources. Furthermore, the developed workflow process is used to formulate the interaction between resources.

3.2.2 Multi-Agent Based Resource Allocation Development

The literature review revealed the fact that multi agent-based models are well-suited for studying human resources' behaviors, formulating their responsibilities, and their interrelationships subject to a dynamic environment such as a hospital. The purpose of MAFMS development is to automate resource coordination processes. MAFMS is developed to integrate the workflow process with resource allocation planning. To achieve this purpose, human resources are allocated to the maintenance orders along the workflow process.

First, human resources and building components are defined as agents. MAFMS consists of six kinds of agents, i.e., work reception and coordinators, facility managers, team coordinators, corrective maintenance resources, preventive maintenance resources, and building components. This model deals with the interactions among human resources and building components through the workflow process. Consequently, rules are set that regulate the interaction between agents based on the workflow process. More details will be given in Section 4.2.2.

3.2.3 MAFMS Architecture Development

MAFMS has a distributed system architecture. Distributed systems architecture consists of independent computers that are connected over a network as a single integrated system. This phase describes the architecture of the MAFMS. UML diagrams are employed to define MAFMS architecture. UML diagrams present different elements of the system for developers. Classes, components, and network structure of MAFMS are illustrated with UML diagrams in Section 4.2.3.

3.3 Agent-based Simulation Model

The performance of the proposed MAFMS (Model 1) has been demonstrated by developing a simulation model for a case study. The simulation model is implemented in Anylogic 6.7.4 (XJ Technologies 2014). The purpose of the MARAS model is to simulate and analyze the workflow and resource allocation process. Facility managers and decision-makers can benefit from the proposed simulation model as follows:

1- Simulate the dynamic environment of building components repair and maintenance;
2- Estimate the resource utilization for a specified time;

3- Measure the performance (uptime and downtime) of the building components.

In order to achieve the objectives of the MARAS model, three phases including (1) data collection (Section 3.3.1), (2) modeling workflow process (Section 3.3.2), and (3) modeling MARAS (Section 3.3.3) are designed. Models 2 and 3 are explained in Chapter 5.

3.3.1 Data Characteristics

The first step in developing simulation models is data collection. Several research methods have been used to collect data for development, testing and validation in this study, including expert interviews, conducting an online survey, and requesting maintenance data from a case study. Appendices A, C, and E show samples of data collected from interviews and the survey. Additional data was provided by FM of Madar hospital in form of Excel sheets including information on work orders, organizational charts, architectural plans, preventive maintenance schedules, and resource work schedules. A description of data is presented in Section 5.2.1.

This data is used as input in the simulation and optimization model. More details are provided in Section 5.2.1.

3.3.2 Workflow Process Model

Modeling workflow process as DES. Simulation model development includes the following steps: definition, abstraction and simulation. The workflow process is abstracted into a discrete event model and Anylogic is used to simulate the work process in maintenance management. The DES model is described in detail in Section 5.2.2.

3.3.3 Modeling Multi-Agent Resource Allocation Simulation (MARAS)

Maintenance resource allocation is an interactive, dynamic, and complex task that can be simplified using MAS as an analytical decision-making tool. As MARAS model regulates coordination between resource agents based on the workflow process. In order to develop such a model, building components and human resource behaviors are abstracted and modeled. The MARAS model is simulated using the ABM method in Anylogic. Sensitivity analysis method is used to validate the developed simulation model. Section 5.2.3, describes these procedures in detail.

3.4 Simulation-Based Optimization Model

As explained in Section 1.2, it becomes essential to develop a novel approach to handle the dynamic maintenance environment while achieving optimal utilization of the resources subject to time and performance in hospitals. Therefore, the SBO model is developed and several resource combinations are tested to generate a near-optimal resource allocation plan. The third model can be used to identify the near-optimal number of resources while minimizing down-time of building services. Therefore, facility managers can re-engineer the resource allocation plan using the SBO. Section 5.2.4 describes modeling of the SBO model in more detail.

3.5 Summary

An overview of the proposed method was presented in this chapter. In order to realize the objectives of the proposed method, three models are developed. In summary, the main achievement of the proposed method is the development of an order tracking-resource allocation system, which combines the fragmented information at the different levels of maintenance management. This integration allows for a structured exchange of information. This system enables the facility manager to make timely decisions efficiently. As a result, delays in responding to maintenance requests are reduced, which can indirectly result in enhancing the patients' satisfaction.

To fulfill this objective, three models have been developed. The first model is MAFMS. This system is developed to manage workflow and allocate resources for maintenance activities by using the MAS approach. This model is explained in Chapter 4. Consequently, MARAS model, and SBO model are developed and performed to simulate and optimize the workflow process and resource allocation. These models are explained in Chapter 5.

CHAPTER 4. DEVELOPING AN AUTOMATED MULTI-AGENT FACILITY MANAGEMENT SYSTEM

4.1 Background

As mentioned in Sections 2.2 and 2.3, the major problems of resource allocation include unforeseen failures of the systems or building components, daily incoming maintenance orders, poor arrangement of the orders in the queue, inefficient assignment of orders to resources, inefficient maintenance schedules, inefficient order recording, and tracking system, and the insufficiency of the access to pertinent data, including the status and availability of resources. Therefore, it is necessary to prevent and/or reduce maintenance delays by improving the maintenance workflow and resource allocation process.

This chapter is a marginally modified version of "Maintenance workflow management in hospitals: An automated multi-agent facility management system" published in *Journal of Building Engineering* (Yousefli et al. 2020) and has been reproduced here. This chapter aims to develop a facility management system to respond to the aforementioned issues in near real-time and handles dynamic workflow process for facility managers in hospitals. The developed system facilitates the management of the workflow and resource allocation process and expedites the updating of the maintenance schedule for improved time effectiveness. The developed MAFMS formulates the coordination among resources (facility managers, service crews, and supervisors). The MAFMS improves communication among resources by integrating and automating the workflow process with the resource allocation plan. This integration and automation reduce the movement of resources to the FM office for ordering and reporting. So the response time of resources to unexpected maintenance requests is decreased remarkably. To demonstrate the applicability of the proposed system, a multi-agent simulation model is developed.

This chapter consists of three phases: workflow process development (Phase 1); multi-agent based resource allocation development (Phase 2); and MAFMS development (Phase 3). Chapter 4 is organized into sections that include the proposed methodology (Section 4.2); implementation and case study (Section 4.3); results and discussion (Section 4.4); and finally, summary and conclusions (Section 4.5).

4.2 Proposed Methodology

The proposed methodology has three phases as shown in Figure 4-1: (1) developing workflow process; (2) defining the components of the multi-agent based resource allocation process; and (3) proposing distributed system architecture and system modeling.

The workflow process is developed based on the service management flow in typical hospitals (Phase 1). In Phase 1, a workflow process is developed to facilitate the arrangement of maintenance orders in appropriate queues, namely coordination, high priority, low priority, scheduled, execution, and supervision queues. Then multi-agent based resource allocation process is developed (Phase 2). The goal of this phase is defining agents, proposing a set of rules to form the agents' behavior, and defining the communication between agents to accomplished maintenance orders. Finally, the system development process is explained in Phase 3. In Phase 3, UML diagrams are developed to design the MAFMS architecture, namely the class diagram, component diagram, network diagram, use case diagram, and sequence diagrams.

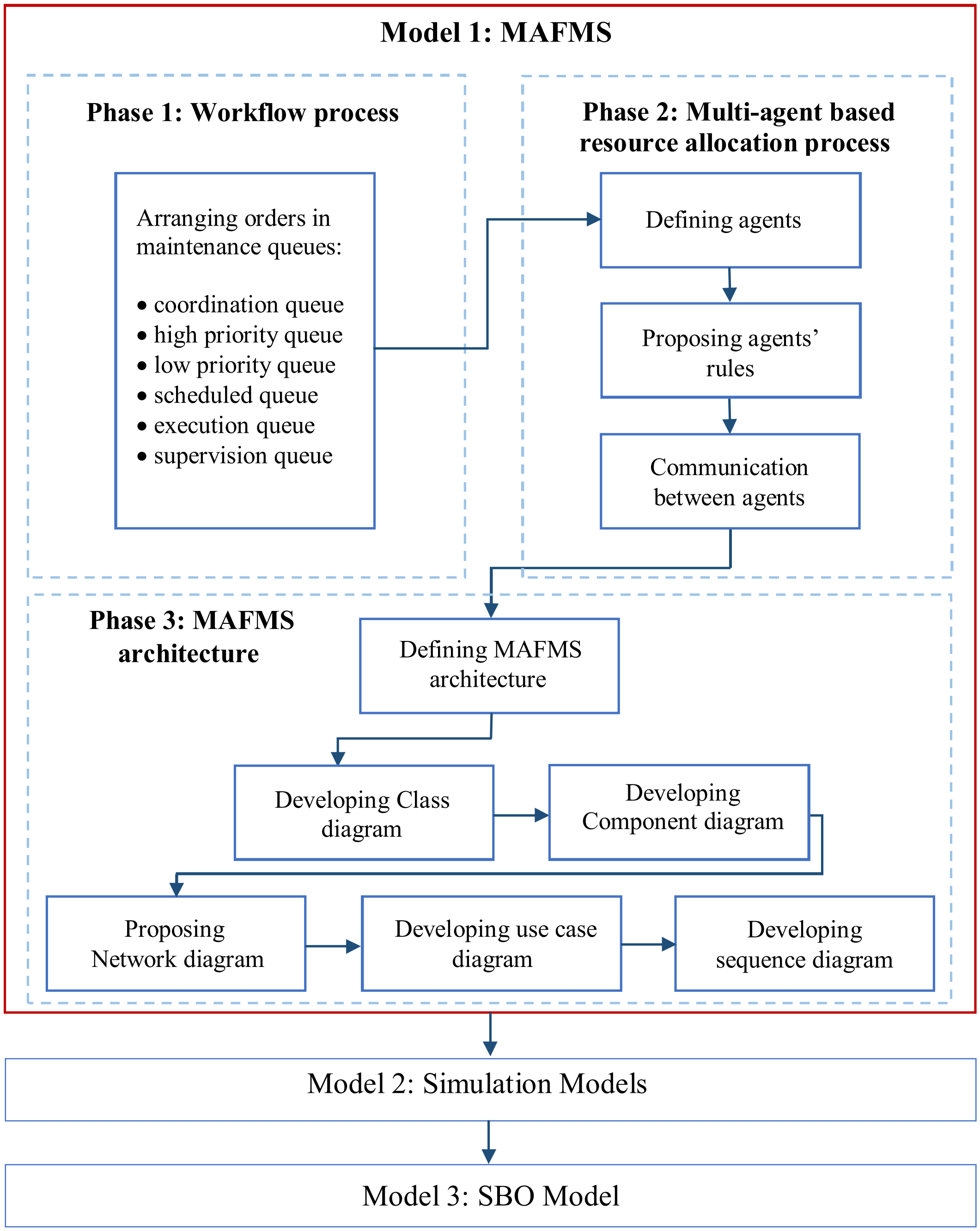


Figure 4-1. Architecture of the proposed methodology for MAFMS (Model 1).

4.2.1 Workflow Process (Phase 1)

The workflow process consists of a sequence of events and decisions that must be made to organize and execute maintenance orders. In this phase, activity diagrams are used to show the proposed workflow.

4.2.1.1 Arrangement of orders in queues

This workflow process is based on the service management flow in typical hospitals (Sharma et al. 2007), which is explained in Section 2.2.3. However, the proposed workflow process in this study adds the prioritization and resource allocation steps to the service management flow. The proposed workflow process includes: (1) order registration and ascertainment; (2) order prioritization; (3) resource allocation; (4) execution; and (5) supervision and documentation process. For each decision process, related activity diagrams are developed as shown in Figures 4-2, 4-3, 4-4, 4-5, and 4-6. Figure 4-2 illustrates the registration and ascertainment process. Once an order is registered, a decision must be made to reject or keep the order in the coordination queue. The registration activity diagram will be used to make the list of accepted orders, which will be prioritized in the next step.

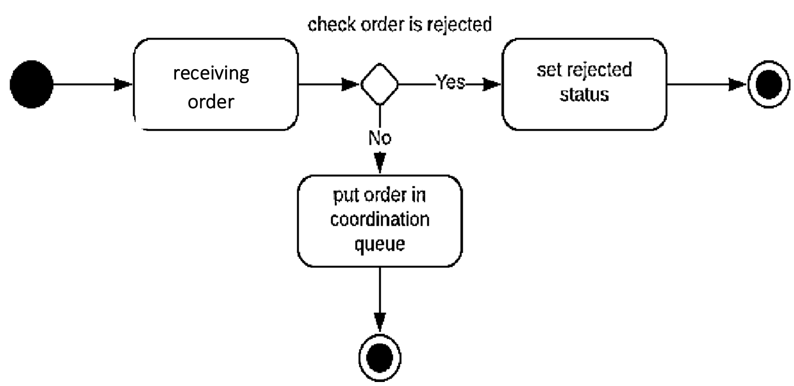


Figure 4-2. Registration and ascertainment activity diagram.

Afterward, the selected orders will be prioritized and allocated to high, low or schedule allocation queue. For this purpose, several factors should be considered, including the emergency level, Latest Starting Time (LST) of the order, and preventive maintenance schedule as defined in Figure 4-3.

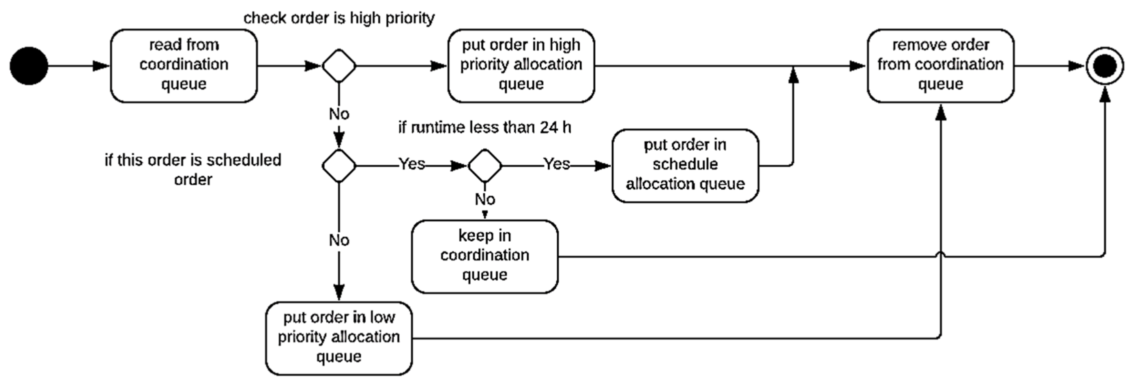


Figure 4-3. Checking priority activity diagram.

Consequently, relevant resources are allocated to carry out orders. During the resource allocation, orders are read from high to low priority allocation queue as well as scheduled queue, then assigned to the related resource considering the maintenance strategic plan (in-house vs. outsourced) and the availability of the resources. Subsequently, the orders are put in an execution queue as shown in Figure 4-5.

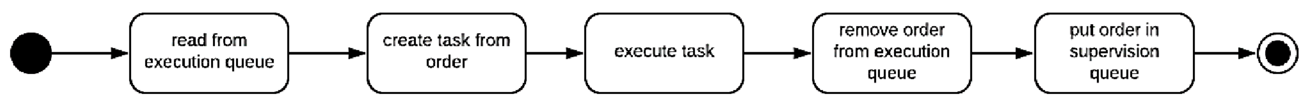


Figure 4-4. Execution activity diagram

In the execution activity diagram, orders are divided into sub-tasks and after execution, orders are removed from the execution queue and added to the supervision queue as shown in Figure 4-4. The supervision-documentation activity diagram is defined to control the quality of maintenance performance. At the end, if the order has been executed satisfactory, it will be removed from the execution queue, and then, a detailed report (containing the work performance) is provided for documentation; otherwise, the order will be added to the coordination queue for rework as shown in Figure 4-6.

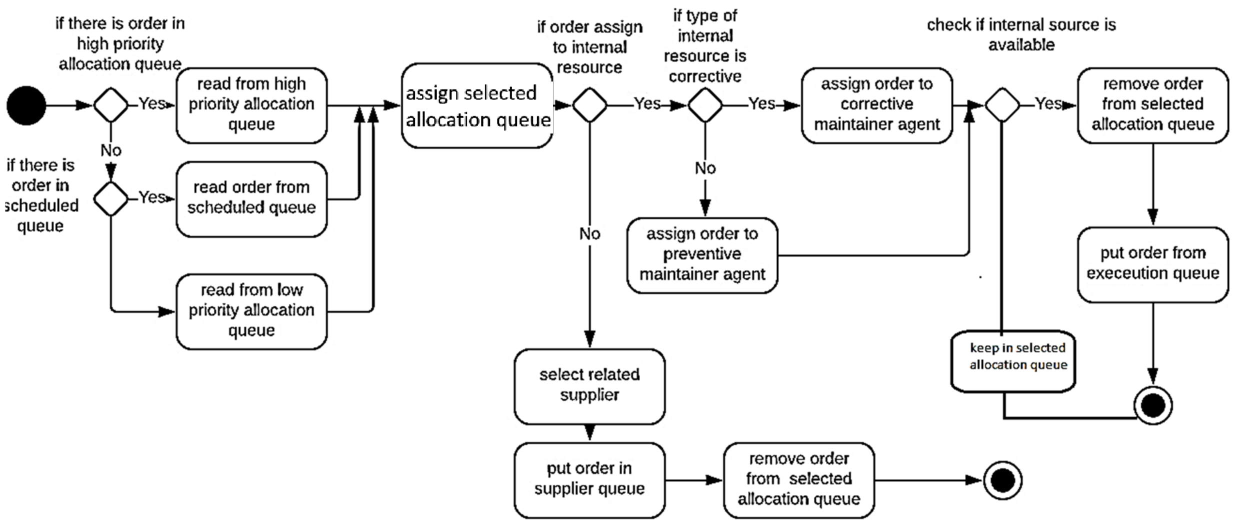


Figure 4-5. Resource allocation activity diagram, FMA portal, and resource allocation.

MAFMS is developed to integrate the maintenance workflow process with resource allocation planning. For this purpose, in next phase, human resources are allocated to the maintenance orders along the workflow process.

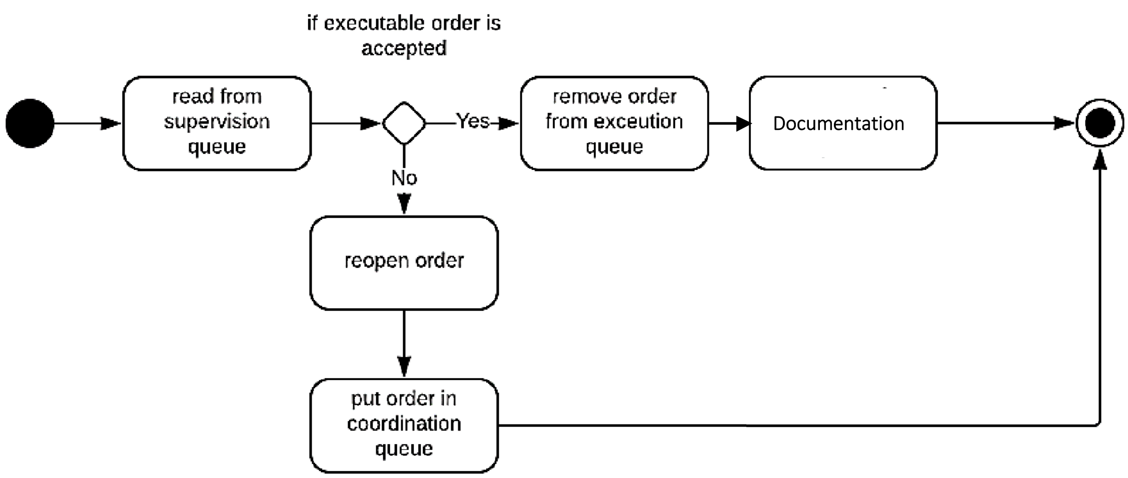


Figure 4-6. Supervision and documentation activity diagram.

4.2.2 Multi-Agent Based Resource Allocation Process (Phase 2)

This phase focuses on translating the resource allocation process into an agent-based schema. This phase consists of three steps; defining agents, proposing agents'rules, defining the communication between agents.

4.2.2.1 Defining agents

In this study, agents are classified into two main categories, which are human resources and building components. Human resource agents are defined according to different levels of maintenance management. Initially, the human resource agents including: (1) Work Receiver/Coordinator Agent (WRCA); (2) Facility Manager Agent (FMA); (3) Corrective Maintenance Agent (CMA); (4) Preventive Maintenance Agent (PMA); (5) Team Coordinator Agent (TCA); and (6) Supplier Agent (SA) are developed in the first step of Phase 2. Then Building Component Agents (BCAs) are proposed, which are different building components (e.g., elevator and HVAC). BCAs have different behaviors, i.e., operating, failed, repair, and replacement.

4.2.2.2 Proposing agents' rules

Subsequently in the second step of Phase 2, rules are set to form the agents' behavior. These rules are established based on the repetitive nature of maintenance activities and will govern the allocation of human resources as shown in Table 4-1. According to responses from the interview, survey results, review of organizational charts, and other organizational documents, rules are set for agents to shape their behaviors. The rules of each agent vary depending on the responsibilities of the agent. For example, according to Q20 in Appendix E, PMA must inspect elevators monthly, every six months, and annually. For each step related human resource agent(s) is allocated, i.e., (1) WRCA and TCA for registration, ascertainment, and prioritization; (2) FMA for planning and resource allocation; (3) CMA and PMA for execution; (4) TCA for supervision; and finally (5) WRCA for documentation. WRCA has to: (1) track the status of orders; (2) add and remove orders in the different queues of maintenance management process; and (3) update these queues.

It shall be noted that the rules are defined on the assumption that agents have rational behaviors. Some (human) agents may be more committed to work and dedicate themselves to work or in the opposite way, be less committed. Agents work according to a work schedule in line with standard number of working hours per day and per week as shown in Figure 5-11. In this thesis, the agent behavior is assumed to be controlled by a developed set of rules. It shall be mentioned that, at this stage, we did not consider a self-learning capability for agents such that they can set up rules by themselves. The aim of decentralization is to speed up data processing but it does not imply that the agents are intelligent and they can change their own behaviors.

Table 4-1. Rules for agent behaviors in the MAFMS structure.

Workflow process	**Agent**	**Agent behavior descriptions**	**Agent's goals**
Registration, Ascertainment, and Prioritization	WRCA	• Add order to coordination queue	• Registering orders to the coordination queue • Send order to FMA
	TCA	• Add order to coordination queue • Remove order from coordination queue (rejection) • Add order to high priority, low priority, or scheduled queue	• Inspecting • Verify • Prioritize • Place orders in appropriate queues
Planning and Resources Allocation	FMA	• Checking preventive schedule and resource work schedule before assign order • Check the resource availability • Assign order to available TCA • Remove order from the high or low priority queue and add to the allocation queue • Assign accepted order to available CMA or PMA	• Meeting maintenance needs on time • Coordinate the resources to reduce the operation time
Execution	CMA	• Remove order from the high priority queue and add to the execution queue • Remove order from execution queue and add to supervision queue	• Repair or replace the BCA
	PMA	• Remove order from scheduled queue and add to the execution queue • Inspect BCAs based on the preventive maintenance schedule • Remove order from execution queue after the inspection and add to supervision queue	• Routine maintenance based on preventive schedule
Supervision and documentation	TCA	• Remove order from supervision queue • Add order to coordination queue	• Evaluate the quality of performance
	WRCA	• Record maintenance information	• Documenting information

4.2.2.3 Communication between agents

Accordingly in the third step of Phase 2, communications between agents are defined. Agents interact with each other to accomplished maintenance orders based on the proposed workflow framework. WRCA records orders, which are sent from the failed BCA. Then FMA notifies TCA to inspect and verify the correctness of the assigned order. If the order is accepted (Figure 4-2), TCA prioritizes the order based on a visual inspection and subjective rating. TCA specifies the type of priority, which includes high and low priority as shown in Figure 4-3. TCA also determines the type of tasks and documents this before submitting the inspection report. After receiving the order confirmation, FMA allocates the available resources to the order as shown in Figure 4-5. Each order may include several tasks. The FMA should check the order assigned date with the work schedule of the resources before the resource allocation. The selected CMA receives notification and logs on to the system to view the assigned orders. CMA should consider the Latest Starting Time (LST) and the Earliest Starting Time (EST) of the order, to execute the order in proper time as shown in Figure 4-4. CMA must enter the executed date and submit the report to the system. TCA evaluates the quality of the performance and closes the order if approved. If the resource performance was not acceptable, the agent would reopen the status of the order as shown in Figure 4-6.

4.2.3 MAFMS Architecture Development (Phase 3)

Phase 3 discusses the architecture and modeling of the MAFMS. This phase has six steps as follows:

Step 1 is defining MAFMS architecture. As explained in Section 2.3.4, four types of distributed architectures are discussed. According to Salah et al. (2017), the microservices architecture is a set of smaller independent services that each microservice can be deployed on a different server. Therefore, if a server crashes, another server can be replaced, so this architecture results in less time to receive response and increase system performance. In this regard, microservice architecture is chosen to develop MAFMS among different types of distributed systems architecture. Visual modeling is used to define the MAFMS architecture, classes, components, and network structure independently of the implementation language.

Step 2 is developing Class diagram. UML class diagram is used to define the different classes of the MAFMS. The UML class diagram constructs, documents and visualizes the MAFMS. Consequently in Step 3, the component diagram developed to show how components are assembled to form the component-based MAFMS. MAFMS network architecture diagram is developed in Step 4 to illustrate the connection between different components of the network. The distributed resource allocation system is formed by a plurality of computers that are connected through a computer network. Relevant resources are coupled to computers to perform various actions.

Subsequently in Step 5, a use case diagram, which is categorized as UML behavioral diagram has been developed to describe the collaborations between the users (i.e., FMA, TCA, CMA, PMA, and SA) of the system with MAFMS. Using a behavioral diagram and two interaction diagrams facilitates the transition from the system development process to modeling workflow process and MARAS. Finally in Step 6, sequence diagrams, which are categorized as UML interaction diagrams, have been developed to visualize the interaction and communication between agents (human resources and building components) to reach corrective and preventive maintenance goals. The sequence diagram also facilitates tracking and modifying the maintenance workflow process with a message sequence chart.

4.3 Implementation and Case Study

The proposed MAFMS is implemented to direct a dynamic workflow process for facility managers in a case study hospital. From an implementation perspective, it shall be mentioned that the UML diagrams have been developed using Visual Paradigm Enterprise Edition 16.1. A Java programming language with Eclipse IDE tool is then used to develop WRCA, FMA, TCA, CMA, and PMA. Finally, Anylogic software is used to simulate the MAFMS on an Intel Core i7 PC with 16 GB of RAM.

Data from the case study hospital is used to develop and validate the simulation models as well as the SBO. As mentioned earlier, organizational charts, architectural plans, work order excel file, resource work schedules, and preventive maintenance schedules of Madar hospital are used to provide inputs to the simulation models.

Madar Hospital is a private hospital built on 8,000 m^2 of land, located in Sajjad, Mashhad, Iran. The building's total floor area is 7,800 m^2. This hospital will be expanded to 14,000 m^2. The board is planning to build the second phase of the hospital in near future. It is an eight-storey building that was built in the year 2000 (20 years ago). This hospital has been selected because of its building characteristics, its health care services, and its special location in the region. This hospital building is gradually deteriorating, which could outstrip available resources and diminish allocated maintenance budgets. As a result of deferred maintenance, failures are being accumulated over time.

Besides that, this hospital has generic building characteristics in terms of building age, number of floors, floor area, number of wards, and number of beds. This hospital, with 120 patient beds and an average of 200 out-patients per day, was analyzed as a case study. Similar to all the other hospitals, there are key areas in this hospital, including, Regular Rooms (RRs), Operating Rooms (ORs), Intensive-Care Units (ICUs), Emergency Rooms (ERs), and FM department.

A centralized maintenance management system has been implemented at this hospital, which has the shortcomings discussed, earlier. In the light of the above facts and that the hospital is a private one, the board has shown interest in improving maintenance management. So, the FM department of this hospital has provided the required data including building components operation and maintenance information, as well as resources information in the excel sheet format. The aim is to not only reduce maintenance delays but also create a service quality competency with respect to other private hospitals in the region.

4.3.1 UML Diagrams

As explained in Section 4.2.3, MAFMS has been developed based on a microservices architecture (Step 1 in Phase 3). A three-tier architecture method has been used to develop each service of MAFMS. The presentation tier consists of a standard Graphical User Interface (GUI). The business logic tier processes data between two other layers and includes web servers. The database tier includes database servers.

In Section 4.2.3, a detailed MAFMS class diagram is developed (Step 2 in Phase 3). In order to develop a class diagram, 22 different classes have been proposed (i.e., Agent, WRCA, FMA, TCA, PMA, CMA, BCA, FM Department, Order, Task, Task Type, Electrical, Mechanical, Architectural, Internal Resource, Account, Resource, Supplier, Supplier Task, Location, Preventive schedule, and Work schedule). Each class has specific attributes and operations as shown in Figure 4-7.

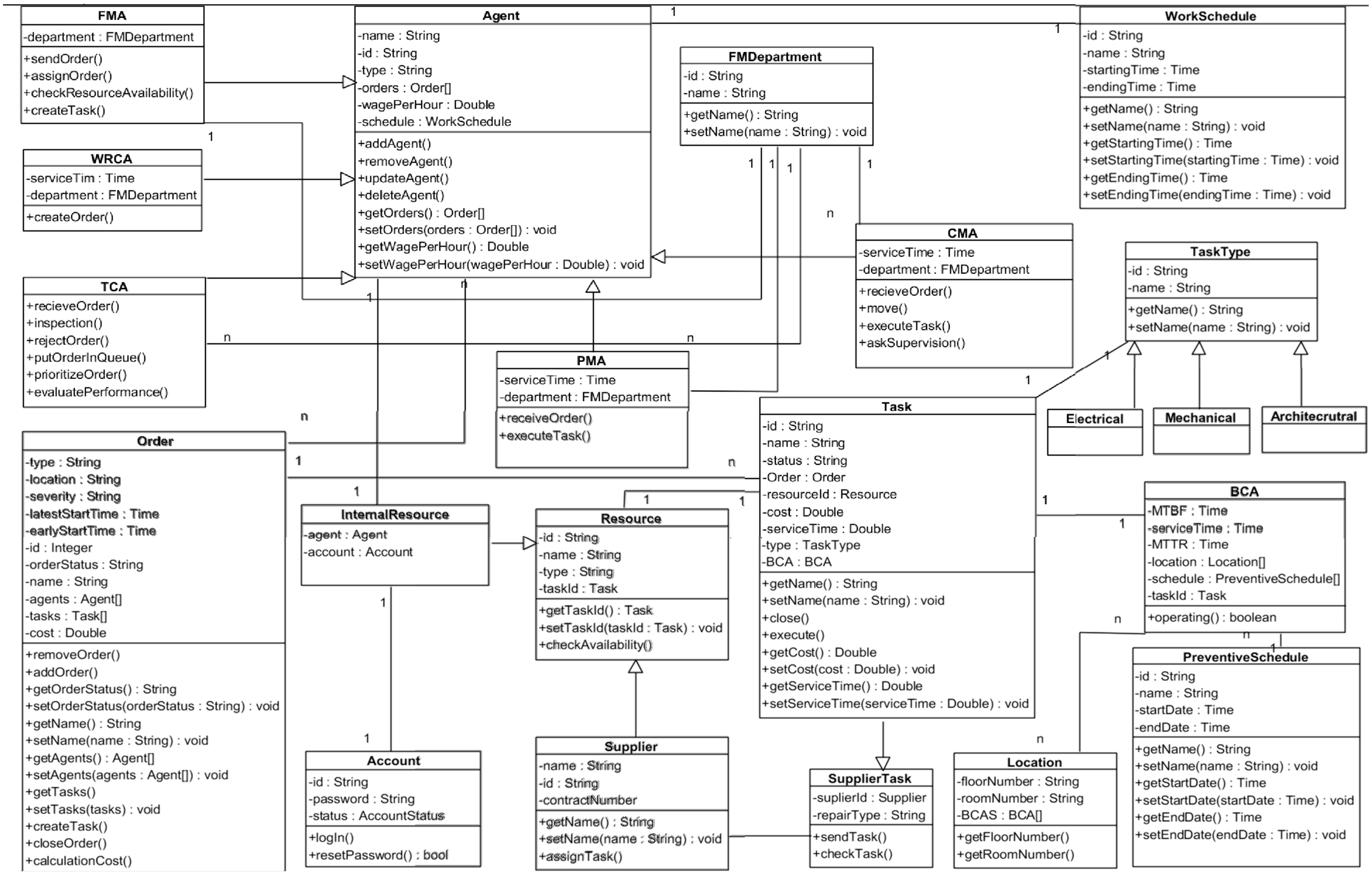


Figure 4-7. MAFMS class diagram (Step 2 in Phase 3).

A component diagram has been developed for MAFMS as shown in Figure 4-8 including registration, planning, and resource allocation, as well as execution and supervision components (Step 3 in Phase 3).

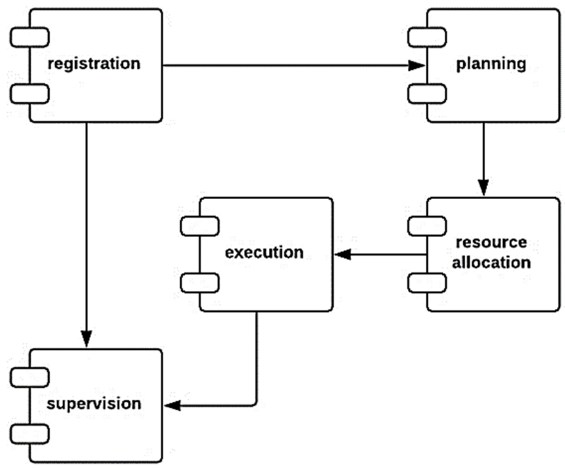


Figure 4-8. MAFMS component diagram (Step 3 in Phase 3).

In Step 4, a network diagram is developed as shown in Figure 4-9. The MAFMS network consists of client tier, internet, firewall, load balancer, web server, nodes (includes system components), message queues, and database (DB). Maintenance orders database, building components database, and resources databases have been provided for the system as well as maintenance schedules. MySQL databases have been used among different Database Management Systems (DBMSs) to store model data due to their high performance and low-cost operation. These databases are constantly updated to provide the required input data for MAFMS. It is worthy to mention that MAFMS services have been implemented in the Java framework Spring Boot.

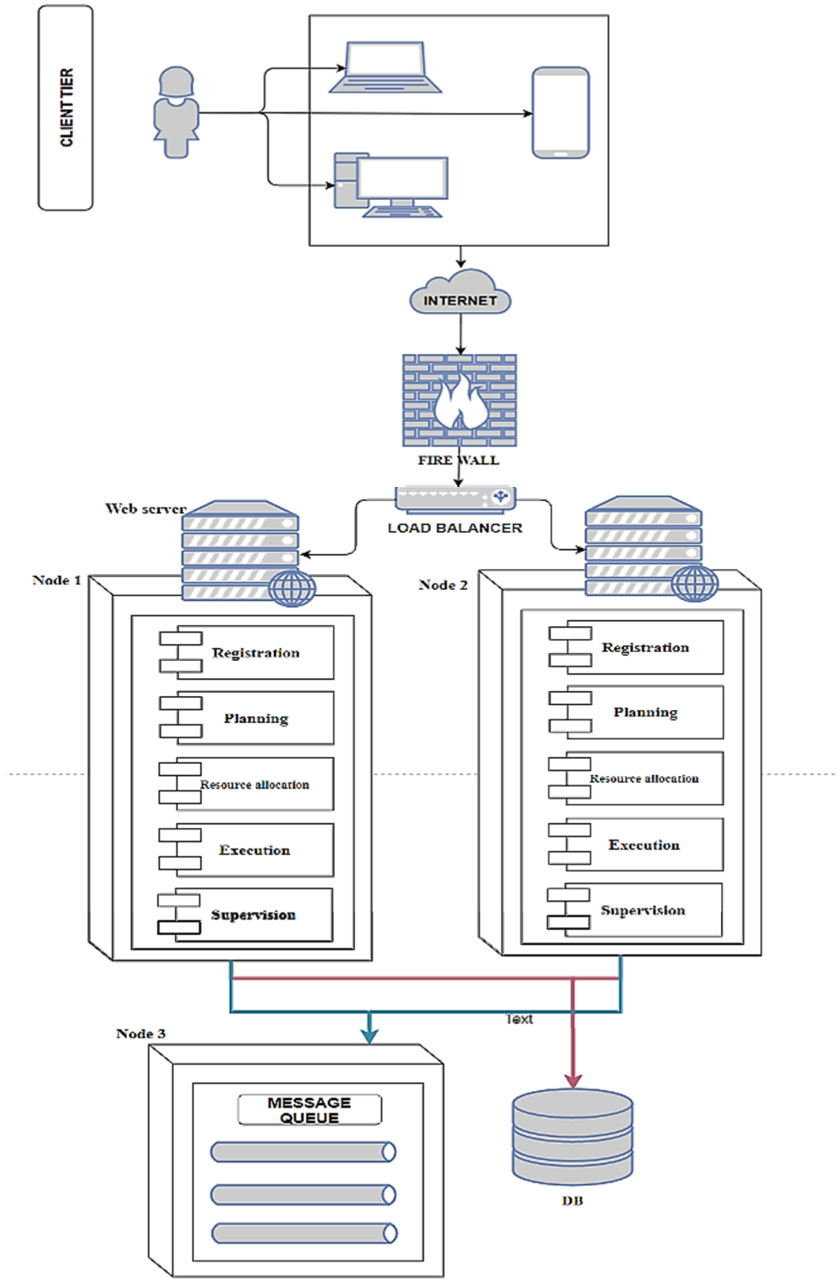


Figure 4-9. MAFMS network diagram (Step 4 in Phase 3).

In Section 4.2.3, a use case diagram is designed as shown in Figure 4-10. The use case diagram is used so that developers can better understand the interaction between the system and its end users (Step 5 in Phase 3). Finally in Step 6, two sequence diagrams are developed in order to visualize the communication between agents in the time sequence. Messages are passed between agents to accomplish maintenance orders. These interactions are simulated in Anylogic 6.7.4 (XJ Technologies 2014). Figure 4-11 shows the sequence diagram for corrective maintenance orders. Figure 4-12 shows the sequence diagram of preventive maintenance orders.

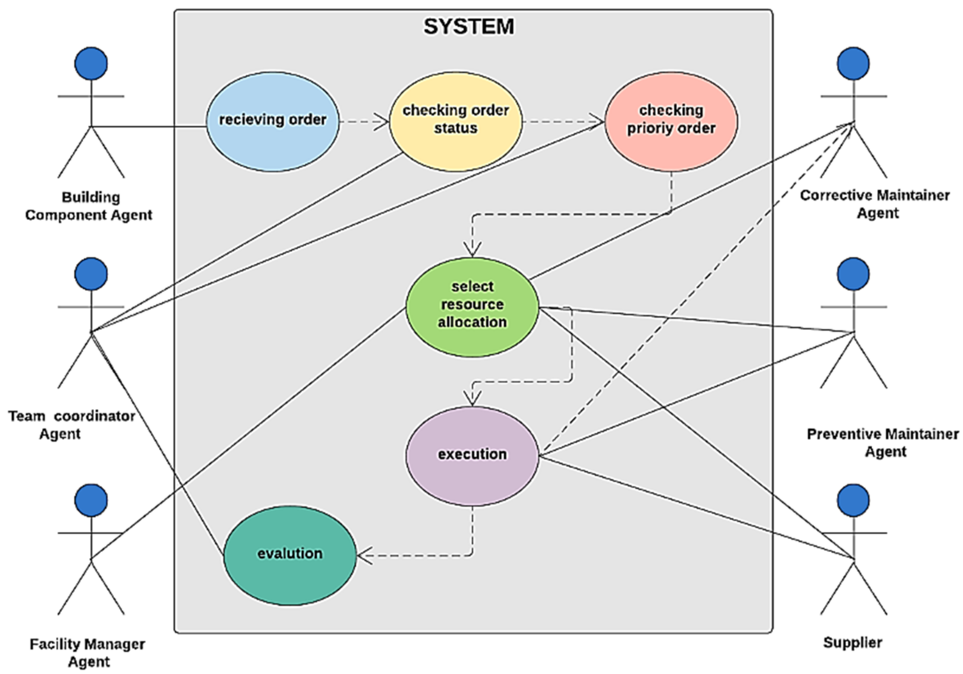


Figure 4-10. MAFMS use case diagram (Step 5 in Phase 3).

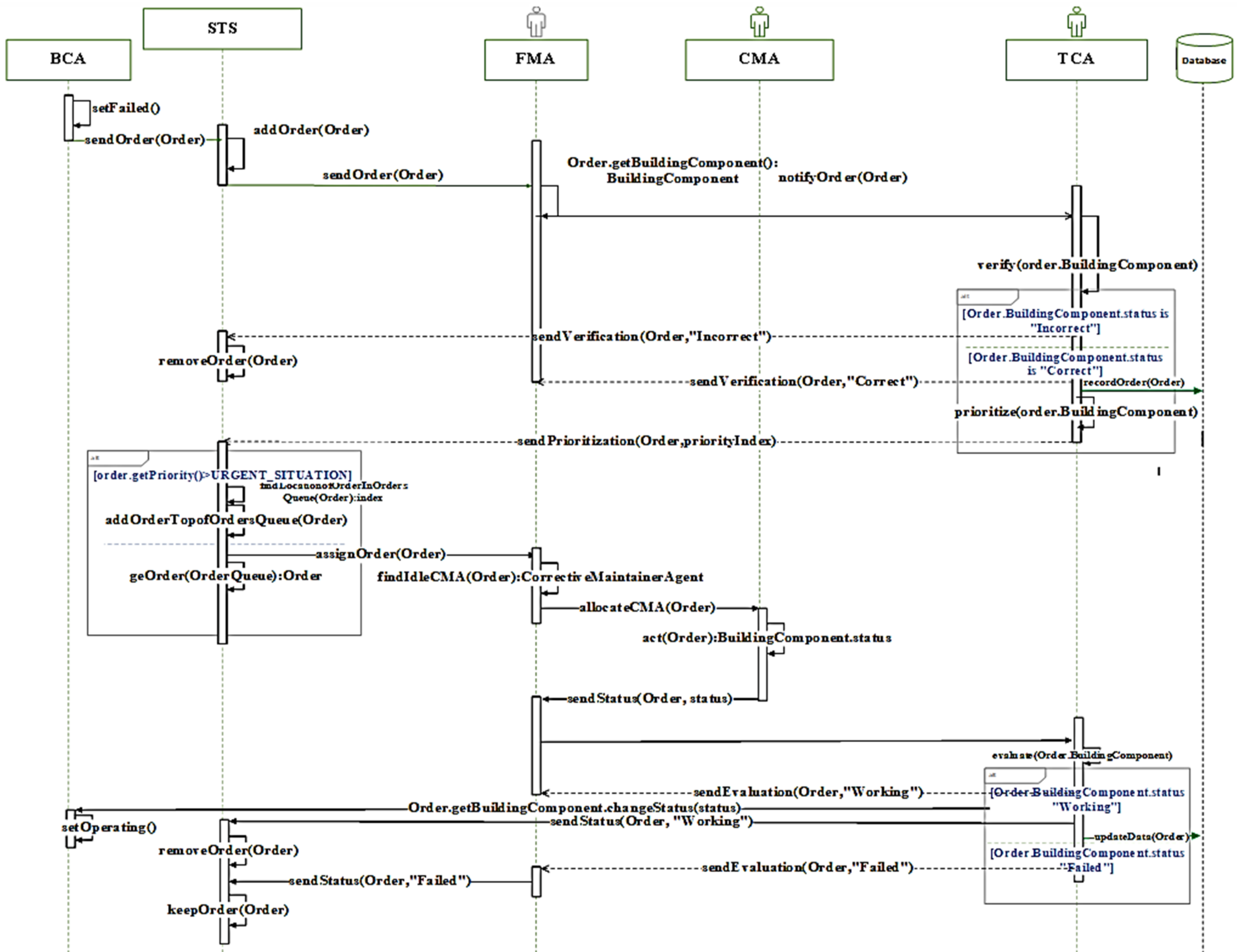


Figure 4-11. MAFMS sequence diagram for corrective maintenance activities (Step 6 in Phase 3).

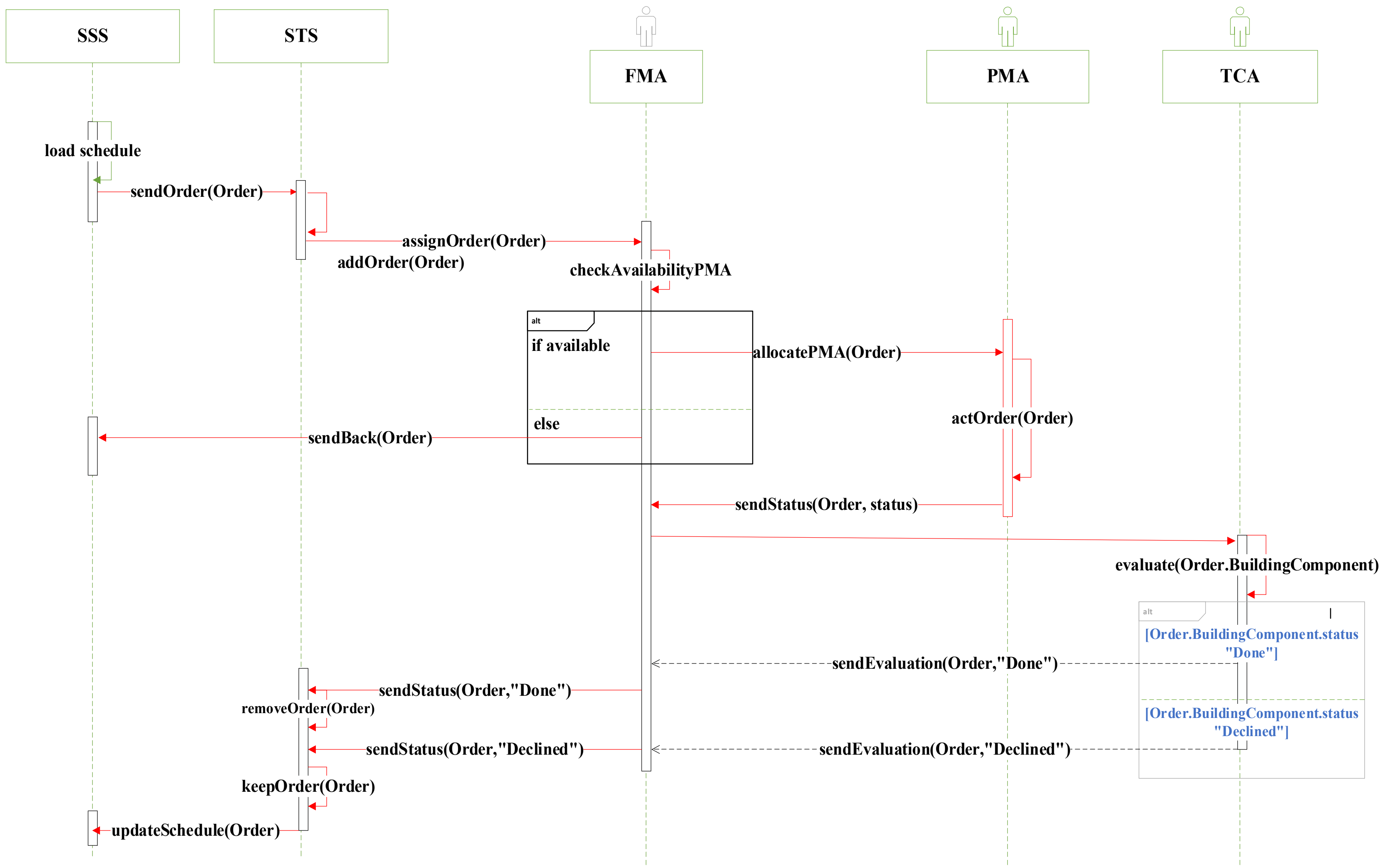


Figure 4-12. MAFMS sequence diagram for preventive maintenance activities (Step 6 in Phase 3).

The proposed model advocates a distributed approach in two ways. Initially, the network diagram incorporates a load balancer mechanism, which distributes orders across different servers as shown in Figure 4-9. This acts as a buffer mechanism such that to prevents a total system failure in case of too many orders or technical problems. Furthermore, this approach facilitates the implementation of smaller distributed work processing units, which reduces computational time, improves response speed of the maintenance system, and facilitates trouble-shooting. Secondly, as shown in Figure 4-11 and Figure 4-12, in an agent-based approach, there are interactions between agents as well as multiple points of decisions corresponding to each agent. Every agent has authority to make decisions according to a predefined list of rules. The main rules are presented in Table 4-1. Therefore, the proposed agent-based approach provides a fully decentralized (and hierarchical) maintenance management.

4.3.2 Implementing Multi-Agent Simulation

To validate the operational benefits of the MAFMS, a multi-agent simulation model is developed and explained in Chapter 5. Simulating the MAFMS shows the function of the system in a real case study. The primary data is obtained from the FM department of the selected hospital. Excel sheets are synthesized to organize and exchange relevant information with the multi-agent simulation. The resource schedule, building component function, and maintenance data are required as input data to the simulation. This data is used to initiate the multi-agent simulation for in-house resource allocation. The multi-agent simulation is built in Anylogic 6.7.4 (XJ Technologies 2014), which is a Java-based ABM platform. Muti-agent simulation shows the interaction between resources and building components at different levels of maintenance management.

4.3.3 Graphical User Interface (GUI) Modeling

The MAFMS user inputs, retrieves, and stores data in the system visually through GUI (presentation tier). The input data is filtered, and a query is sent to the proper database (database tier) with feedback provided to the user (business logic tier). Visual Paradigm Enterprise is then used to design the GUI of the MAFMS. Each resource agent gains access to the system by identifying and authenticating itself. The main purpose of the authentication system is to validate the resources' right to access the system and ensure the security of the system. Since MAFMS is a web-based system, SSO is used to prevent unauthorized access to the system and ensure data security. Every human resource agent can log in to the system by mobile or tablet anywhere in the building. Establishing a Kiosk on any floor could also facilitate using this system. The administration portal is designed to manage the orders, resource agents, and work schedules. In the order section in the admin portal (Figure 4-13), WRCA can view orders at different statuses. Moreover, it can add the new order or remove the rejected order from the system. The order status could be placed, assigned, accepted, rejected, allocated, executed, closed, or reopen in the system. The agent section in the admin portal shows the agent's type includes: FMA, TCA, CMA, PMA, and SA. The work schedule of each agent is defined and kept in this section.

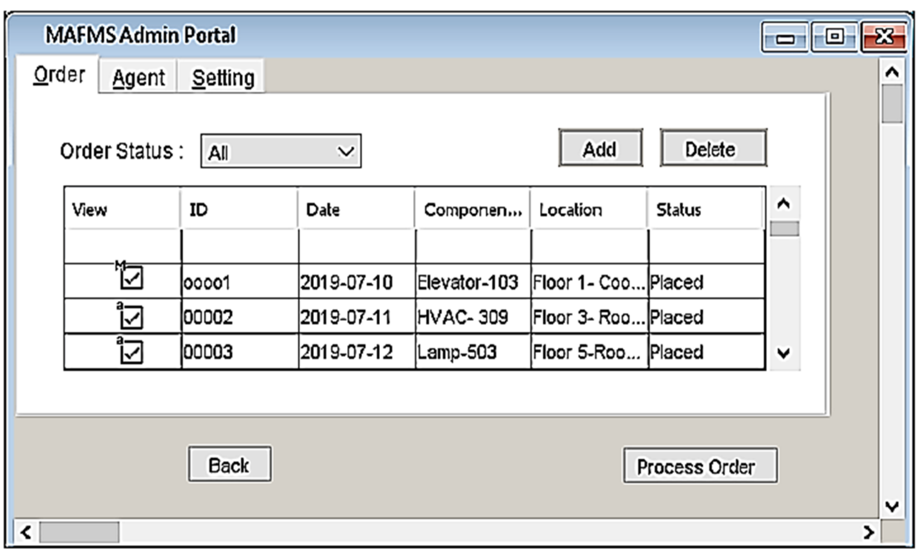


Figure 4-13. MAFMS admin portal (registration)

The setting section of the admin portal includes the list of agents' type, building components, systems, locations, and preventive schedules. FMA logs on to the system and selects order from the combo box, then assigns the order to available TCA. FMA should enter the assigned date into the system manually. TCA logs on to the system and sees the list of assigned orders. The agent moves to the location and inspects the failed component or system. TCA verifies the correctness of the assigned order and checks the level of the order urgency to prioritize the order and facilitate the arrangement of the order in the appropriate queue as shown in Figure 4-14.

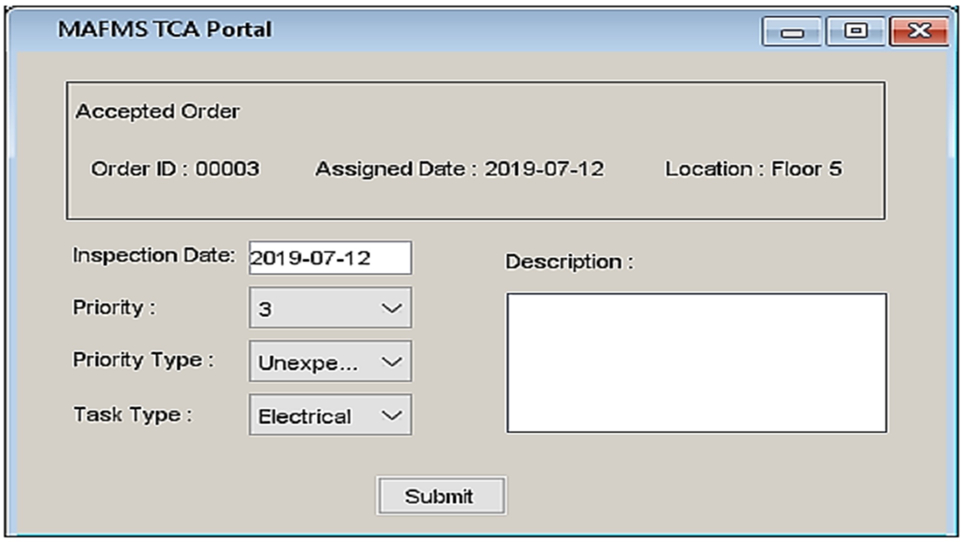


Figure 4-14. TCA portal (checking priority)

The developed simulation model can generate a real-time distribution of all resource agents in different states. Therefore, facility managers can monitor the performance of resources instantly and make decisions by applying the proposed model. In addition, the facility manager can monitor the status of the orders in different queues, estimate the resource utilization, and measure the performance of building components as the results of the simulation. Simulation results could be used to prepare maintenance reports for facility managers. The GUI was designed to enable the facility manager to input, retrieve, and store data within a MARAS as shown in Figure 4-15.

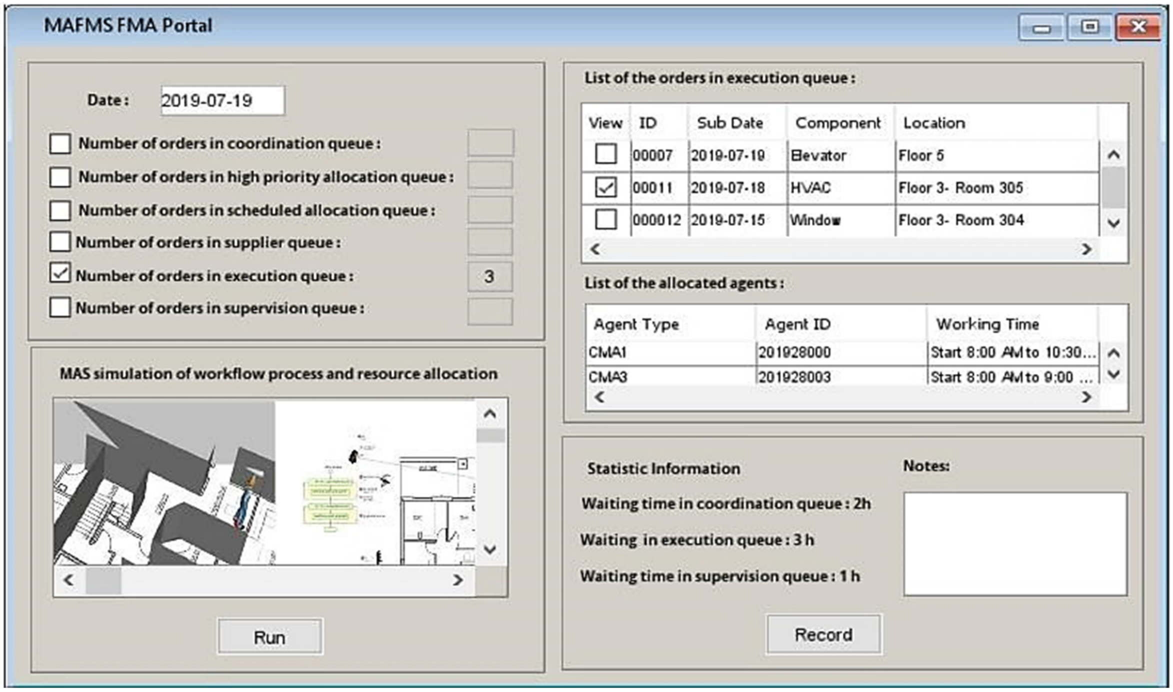


Figure 4-15. MAFMS GUI, simulation and visualization platform.

4.4 Results and Discussion

An automated system is developed for the maintenance management of hospital buildings. The MAFMS is a distributed system, which consists of five components. The workflow process includes several levels of maintenance management, and these levels form the system components. There are resources in each component that pursue their own goals. These intelligence agents are allowed to interact with each other in order to solve the complex problems of workflow management and resource allocation. The MAFMS acts as a dynamic decision support system and is offered to facility managers to better manage the workflow and their resources. The developed MAFMS can follow up on the status of maintenance orders and accelerate maintenance workflow. In the following some of the specialized computer terms that are characteristic of MAFMS will be briefly described:

- MAFMS is a distributed system: Applications contain the separate modules deployed on multiple servers at the time of installation, however, these modules are integrated.

- MAFMS is a component-based system: Component-based systems have the benefits of easy testing, fast maintenance, and upgrading of the system. If a component such as Planning fails in MAFMS, another server will quickly be replaced. Therefore, the requested orders will be switched on to the other server. So, the risk of system failure is reduced.
- MAFMS is on cloud: The system is on the cloud, so, it facilitates access to the system from anywhere. The cloud system eliminates location status for human resources in the building. So, they do not have to go to the FM department to receive an order. Having the database of the MAFMS on the cloud, the data can be shared between different servers. The system allows resources to view, edit, and share maintenance documents. Cloud computing enhances collaboration among resources and reduces paper-based work. The user of the system must have an internet connection to receive the required information and can input the information anytime and anywhere.
- MAFMS is a near real-time system: The system is capable of processing data and responding to user inputs with a delay of only a few minutes. Therefore, the development of a near real-time system almost reduces the resource response time to the requested orders, thus reducing the maintenance delays.

4.5 Summary and Conclusions

In this chapter, an automated and distributed building maintenance management system is introduced to support dynamic workflow management and resource allocation for facility managers in hospital buildings. The MAFMS integrates fragmented information from different sources into a unified system. So the response time of resources to unexpected maintenance requests is significantly decreased. Furthermore, the proposed model formulates the coordination and interactions among resources (facility managers, service crews, and supervisors) and building components through the workflow process. Therefore, this system improves communication between resources and reduces the movement of resources for ordering and reporting to the FM office.

MAFMS is a web-based system that reduces the extent of movement/circulation for human resources across the facilities. In addition, the automation of human resources coordination reduces human resource response time to maintenance orders. MAFMS architecture is visualized in the form of the UML structural diagrams, namely: the class diagram, component diagram, and network diagram. Based on this architecture, it is possible to develop MAFMS for other applications. Five components have been assembled to develop MAFMS as a component-based system. However, to develop an automated outsourcing decision support tool, the system can be expanded by adding some additional components, such as a bidding component. Multi-agent simulation model has been developed to advocate a distributed and dynamic environment for maintenance management under the complexities and uncertainties involved in FM of hospital buildings. A use case diagram and sequence diagrams are developed to show the communication between agents in the Multi-agent simulation. The multi-agent simulation results show that the operating time of elevators is sustaining between 90% - 97%. The proposed can be employed in other hospitals subject to customizations as relate to human resources categories and building components operation and maintenance information.

CHAPTER 5. DEVELOPING AN MULTI-AGENT SIMULATION MODEL FOR MAINTENANCE WORKFLOW MANAGEMENT AND RESOURCE ALLOCATION

5.1 Background

The dynamic nature of FM tasks in hospitals has been explained in Section 2.4. This dynamism is due to the high volume of unexpected failures of building components, the unpredictability of resources and their availability, and changes in schedules, which are specific to non-stop operations of hospital facilities. Simulation models are invaluable tools to solve complex and dynamic problems. Two approaches are recognized for maintenance management modeling, prescriptive approach modeling and performance based modeling, with a focus on the optimization of the resources and performance. This study uses the prescriptive approach to modeling resource planning through simulation. The main reason for this choice is that the resource allocation plan is affected by the behavior of individuals (resources and building components) and the interaction between them.

This chapter is a marginally modified version of "Application of multi-agent simulation for maintenance workflow management and resource allocation in hospital buildings" accepted in the *Journal of Architectural Engineering* (Yousefli et al. 2021). As the resource allocation decisions are made in a dynamic environment (as relate to failure, status of resources, and schedules), in this chapter, two simulation models and a SBO model are developed to address dynamism in maintenance activities at hospitals. The objectives of the developed simulation models are as follows: (1) simulate the dynamic environment of building components repair and maintenance; (2) estimate the resource utilization for a specified time; and (3) measure the performance (uptime and downtime) of the building components.

Chapter 5 is organized into sections that include the proposed methodology (Section 5.2), implementation and case study (Section 5.3), results and discussion (Section 5.4), and finally, summary and conclusions (Section 5.5). In the following section, the development of the proposed simulation model will be introduced and discussed.

5.2 Proposed Methodology

The developed simulation models consist of two components: a workflow process model and a Resource Allocation System (RAS). In this respect, workflow process is modeled using a DES process due to the nature of maintenance request (failure) arrivals. A DES is used to simulate the maintenance process flow while a MAS is used to simulate the process of allocating resources for maintenance activities in hospital buildings. The DES model shows the process for registration, arrangement, and distribution of maintenance tasks (orders) to the appropriate resources. The workflow process model helps to monitor the status of the orders in the different queues for repair, replacement, and maintenance. For the RAS component, a MARAS is developed to simulate different resource allocation scenarios accounting for interactions among various agents (decision-makers) in the maintenance process. A case example is presented to demonstrate the essential features of the developed method. The simulation results show that the implementation of MARAS significantly reduces maintenance delays in the case study. MARAS consists of building components, the facility manager as a decision-maker, corrective and preventive crews as executive resources, and team coordinators as inspectors overseeing allocated resources. It shall be noted that the DES model provides the work flow inputs for the agent-based simulation model. Thus, the DES model and the agent-based model are inter-related. The probabilistic nature of DES model helps in accounting for the likelihood of delays in maintenance activities.

As shown in Figure 5-1, this chapter has two models. Model 2 has three phases, i.e., data collection (Phase 4); modeling workflow process (Phase 5); modeling MARAS (Phase 6). Model 3 has only one Phase, which is performing simulation and optimization (Phase 7). Each phase has several steps, which are explained in more detail. In the first step of Phase 4, the data collection method is explained. In addition, in the second step of phase 4, the collected data is fitted to the model by adjusting maintenance parameters. Phase 5, provides a procedure for developing the DES. This phase has two steps, definition (Step 1 in Phase 5) and abstraction (Step 2 in Phase 5). In this Step a DES is developed to simulate the workflow process. In Phase 6, a procedure for developing the MARAS is proposed. Phase 6 has two steps, modeling the behavior of building component (Step 1 in Phase 6) and modeling resource agents' behavior (Step 2 in Phase 6). For this purpose, ABM has been selected as a robust simulation method. In Phase 6, the MARAS is modeled using Anylogic simulation software (XJ Technologies 2014). Finally, in Model 3, the MARAS is simulated and the results are analyzed (Phase 7). Phase 7, contains five steps: input data to the simulation model (Step 1), run the DES and MARAS simulations (Step 2), validation and deploy the simulation models (Step 3). Steps 2 and 3 have been used to create a baseline model for investigating the current situation and calibration and comparison of results. Concurrently, in Step 4, the SBO is performed. Finally in the second step of Phase 7, the SBO results has been validated and deploy. Detailed explanation of each phase and related steps are described subsequently.

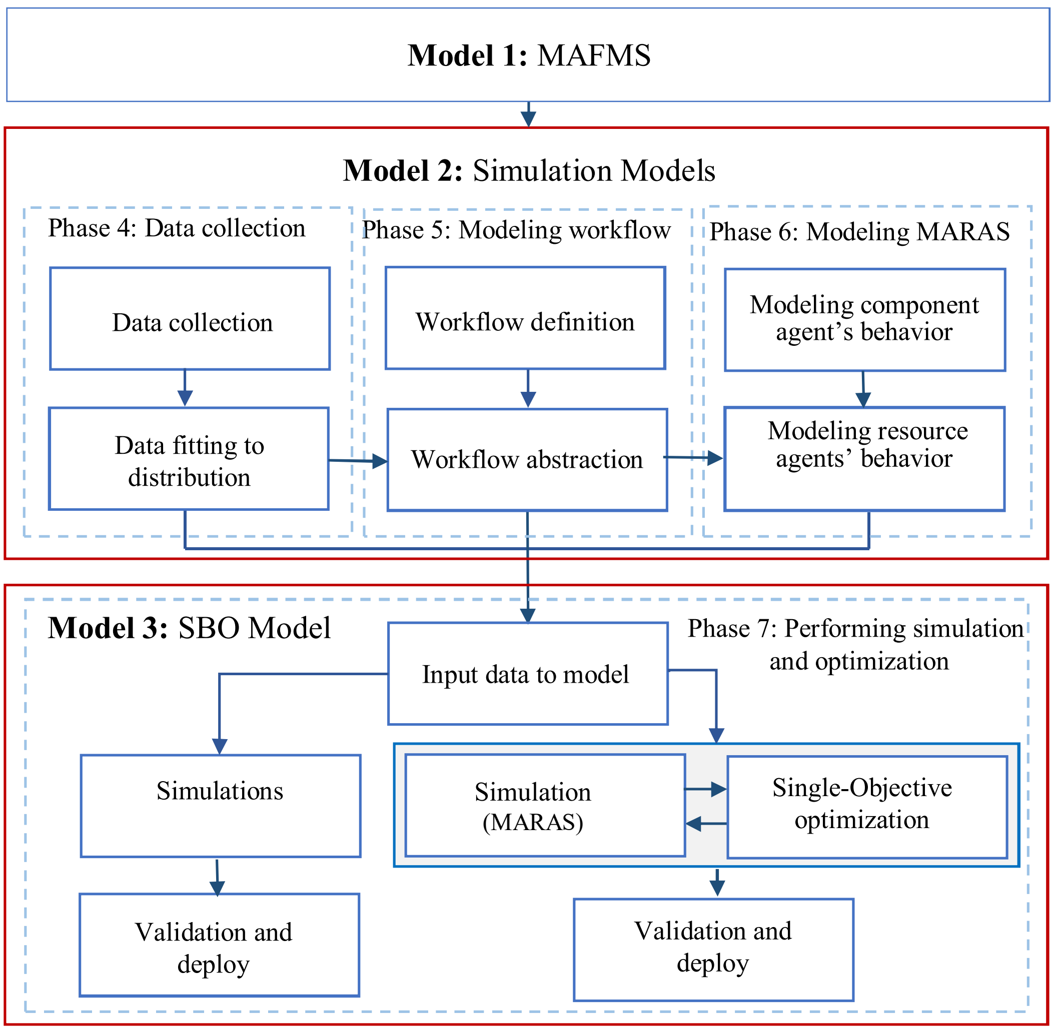


Figure 5-1. Architecture of the proposed methodology for simulation (Model 2) and SBO (Model 3)

5.2.1 Data Collection Strategies, Organization, and Processing (Phase 4)

The process of collecting, organizing, and processing the data is summarized in this section. The collected data is used to develop and implement two simulation models including a DES for workflow management and an ABM for resource allocation as well as SBO model. The nature and element of data and collection strategies are described in the following section.

5.2.1.1 Data Collection Strategies

As shown in Table 5-1, a number of research methods were used for data collection. Expert interviews were conducted with facility managers and maintenance experts working in hospitals and health care centers. The purpose of these meetings and interviews was to understand the current workflow process and resource allocation planning methods in hospital buildings. Interviews were conducted with the FM of Madar hospital. Appendix A shows sample interview questions. In addition to data collected through interviews, an online survey was conducted. The online survey was designed in two parts based on the results of interviews. Appendices B and D show the survey questions. The analysis of the survey results for Parts one and two are shown in Appendices C and E.

Data required for implementation and validation of developed simulation models were obtained from the FM of Madar hospital. Due to confidentiality issues, this information is not listed in this thesis. In addition to FM of Madar hospital, a meeting with FM and maintenance department of Concordia University was conducted. They described the FM strategies adopted at Concordia University and provided the historical data on work orders at EV building. Appendix F shows a sample of work orders collected from Concordia University FM.

5.2.1.1.1 Interviews

Interviews were conducted with facility managers and maintenance staff of several hospitals in Iran, as well as the facility manager of Concordia University. These meetings and interviews were recorded and analyzed. The main purpose of these interviews was to study the current process of resource allocation, workflow management, maintenance planning, scheduling, inspection and reporting, order prioritization and ranking, repair and replacement, preventive maintenance, and finally information management. In addition, these interviews sought to identify the issues and challenges of current resource allocation methods and justified the need to develop a new method for simulating workflow and resource allocation in maintenance of hospital buildings. It shall be noted that; the interviews and observations help to design the rules that govern resource behaviors in MARAS. A sample of interview questions with Facility Manager of Maternal Hospital is shown in Appendix A.

5.2.1.1.2 Conducting Survey

The results of the survey have been used to develop simulation models from scratch. Facility managers from Canadian and Iranian hospitals participated in the survey. 30 multiple choice questions were distributed via email to more than 30 people, however 20 respondents filled out the survey. The main purpose of conducting the survey was to evaluate the current process of resource allocation and workflow management in hospitals and healthcare centers and use the collected data to model the process of resource allocation of the hospital building in simulation software. The structured questionnaire was prepared to evaluate the effectiveness of maintenance workflow management and resource allocation in public and private hospitals. This questionnaire seeks information from experts in maintenance and FM of hospitals and medical facilities. Distribution of the survey was directed to facility managers of hospital buildings. To analyze survey results Qualtrics' analytical tools were used. Interviews and survey findings are used as input data to multi-agent simulation model. The contents of 30 survey questions are summarized as follows:

1) Building information includes: (1) total square footage; (2) age of building; (3) number of visitors of building; and (4) number of elevators in the building;
2) Type of maintenance management method includes: (1) study-based; (2) automated service management process; and (3) CMMS;
3) Work orders information includes: (1) number of work orders received per day on average; (2) the inter-arrival time (in hours) of receiving work orders; (3) the average waiting time (in minutes) for each order in the registration queue to receive response from the service crew; (4) the average waiting time (minutes) for each order in the supervision queue to receive responses from the supervisor; (5) the percentages of rejected work orders; and (6) the percentage of work orders within a year, which are related to repair and preventive maintenance of elevators;
4) Prioritization of orders (the queuing discipline) includes: (1) FIFO (first-in, first-out); (2)

LIFO (last-in, first-out); and (3) Priority-based;

5) Human resource allocation includes: (1) the percentage of the corrective maintenance activities (repair and replacement) and preventive maintenance activities performed by in-house personnel and contractors and (2) the number of service crews (i.e., administration, facility manager, supervisor, Corrective Maintenance Resource (CMR), Preventive Maintenance Resource (PMR), and contractor) used for elevator repairs or maintenance;

6) Time spent by service crews in the workflow process includes: (1) registration; (2) planning; (3) resource allocation; (4) executing; and (5) supervision and documentation;

7) The total time (in hours) a CMR and a PMR spends on maintenance activities (i.e., repair, replacement, report preparing, movement, waiting in FM office, and exchanging of the information) in a 40 hours-week;

8) Time (in hours) spent by a supervisor on different activities in a period of 40 hours-week;

9) Operation and maintenance information of the elevators includes: (1) age; (2) MTBF; (3) average repair time; (4) checkup times based on a maintenance schedule; (5) decision criteria for replacement (i.e., age, number of repairs, number of maintenance interventions, and maintenance cost); (6) average reworked time spent on repair of an elevator (per hours); (7) number of hours (on average) spent by service crews for elevators repair or maintenance; and (8) Risk Priority Number (RPN) (i.e., likelihood of occurrence, likelihood of detection, and severity of impact) (Xiao et al. 2011) for elevator failure.

Appendices C and E show the survey results analysis and explain how these results were used in simulation models.

5.2.1.1.3 Data collected from the Case Study

To implement the simulation model in Anylogic software, real maintenance data provided by Madar Hospital FM department were used. The required information has been extracted from FM organizational chart, architectural plans, work orders excel sheets, resource work schedules, and preventive maintenance schedules. It should be mentioned that these documents and raw data could not be attached to this thesis because a Non-Disclosure Agreement (NDA) has been signed with the FM department of Madar hospital.

FM organizational chart includes the number of human resources, description of responsibilities and tasks of resources and their interrelationships. This information is used to regulate the behavior of resources (set up rules for agent actions) in MARAS (Section 5.2.3). Architectural plans of Madar hospital include information about the location of FM office and the main building components and movement pathways of resources across the building. This information is used to develop the 3D visualizations in MARAS.

Excel worksheets include work number, location of failed building component, type of work, problem code, failure code, description, status date, report date, order status, and working hours.

Table 5-1. Summary of data collection strategies.

Strategies	Purpose	Type of information	Challenges
Interview **Composition of the people participating in the interviews:** 9 people were interviewed. There were facility managers (logistics associate director, administration director, operations director) & service crews (Plumbers and mechanical and electrical engineers) of: - Madar hospital (n=5) - Emamreza hospital (n=2) - Ghaem hospital (n=1) - Concordia university (n=1)	To understand the current processes of resource allocation and workflow management, To identify the issues and challenges, Investigate human resource responsibilities, To set rules that manage resource behaviors in an agent-based simulation model. To develop a method to simulate resource allocation.	**Organizational chart** - structure of organization and relationships - types of HRs - number of HRs - labor hours **Maintenance reports (Excel spreadsheet)** - types of failures - failures frequency - number of failures in a day/week/month/year - type of tasks - failures date - reporting date - repair/replacement time **Preventive maintenance schedule**	- Costly and time-consuming - Manual data entry - Limit sample size - Classification and documentation of scattered and incomplete information - Validation and analysis of information
Survey (Questionnaire) **People participating in the survey:** Facility managers from Canadian and Iranian Hospitals. **Number of questions:** 30 multiple choice questions	To understand the current processes of resource allocation and workflow management in hospitals and healthcare centers, To identify the shortcomings of the current resource allocation methods,	- Building information -Type of maintenance management - Work orders information - Order prioritization policy - Resource allocation method and assessment - Responsibilities of human resources	- Finding experts in the FM department of hospitals and healthcare facilities

Method of distribution: Send emails to more than 30 people, 20 people filled out the survey.	To simulation modeling of the workflow and resource allocation.	- Resources challenges and suggestions	
Case study **(**Madar Hospital) Interview Questioning Observation Study of organizational documents, forms and reports	- To understand the current situation of resource allocation and workflow management in the case study, - To develop the simulation models, - To calibrate the base model, - To develop the SBO model parameters (decision variables, fixed parameters, constraints)	**FM organization chart** **Architectural plans** **Excel sheet** - Work orders information **Resource's work schedule** -Number of resources -Working days/hours and weekends in a year **Preventive schedule** - Dates of routine maintenance tasks - Number of resources - Average time of maintenance	- Access to confidential data - Incomplete historical data

5.2.1.2 Data Organization and Processing

The purpose of data collection is to investigate and review the current methods of resource allocation and workflow management in hospitals and health centers, identify issues and challenges and correspondingly develop simulation models for resource allocation.

In development of simulation models, data from a real case study was required. Therefore, excel data is filtered to display records related to elevator failures at Madar hospital. Elevators at Madar hospital are selected as BCAs (Section 5.3.3), then human resource behaviors related to elevator maintenance activities are simulated. The base model is developed and calibrated to mimic the current situation at the case study hospital. This data is used to model and simulate their maintenance behaviors using Anylogic software.

5.2.1.3 Data Fitting to Distribution

The only way of addressing uncertainty is to incorporate randomness into the developed simulation model. The Anylogic model requires the data as an input to run and analyze the simulation. This random data is used in the form of a distribution, which best fits the data. Distribution fitting is a process that uses an analytical formula to fit a probability distribution to a set of random data, as closely as possible. In this study, data was collected for inter-arrival times of maintenance orders (request) and service times of each maintenance activity in the workflow process. Among a set of probability distribution functions, uniform, triangular, exponential, and Boolean functions are used in the developed simulation model.

A triangular distribution is used when the minimum, maximum, and most probable value (mode) are known. Furthermore, the exponential distribution is used as the inter-arrival times for input streams of maintenance orders (unexpected requests) in the process model. It is assumed that orders occur independently at a constant average rate. For example, at the BCA maintenance behavior state chart, "Failure" transition set the trigger type to Rate. It is assumed that the BCA's failure behavior follows an exponential distribution, with a constant failure rate (MTBF). As explained in Section 2.3, the door system is the highest source of elevator failure; therefore, MTBF for the elevator door system is considered in this study. According to the maintenance data from the case study, this time is 50 days.

5.2.2 Modeling Workflow Process (Phase 5)

Workflow process model shows a process that includes the registration of orders, the arrangement of orders in different maintenance queues, and the allocation of resources to execute these orders. The purpose of developing this model is to minimize the waiting time for orders in different queues for repair, maintenance and inspection. Simulation model development includes the following phases: definition, abstraction and simulation. Each is described subsequently.

5.2.2.1 Workflow process definition

To create such a system, the routine maintenance management process in typical hospitals was studied through interviews with hospital facility managers, and a questionnaire survey (Phase 4).

According to (Sharma et al. 2007) the maintenance management process in typical hospitals consists of several levels, i.e., registration, planning, resource allocation, execution, supervision and documentation. Therefore, the hierarchy of the workflow process includes: (1) registration and ascertainment, (2) prioritization, (3) resource allocation, (4) execution, and (5) supervision and documentation levels as shown in Figure 5-2.

After placing an order in the coordination queue, it must be decided to reject or accept the order. Then, the accepted orders will be prioritized and allocated to a high priority or low priority queue. Appropriate resources are then allocated to accomplish the order. Subsequently, the orders are removed from the high or low priority queue and added to the execution queue to repair or replace the building component. In order to control the quality of the execution, the order is removed from the execution queue and added to the supervision queue. At the end, the executed order is removed from the supervision queue, unless the quality of execution is not satisfactory. In this case, the order is added to the failing queue. Figure 5-3, the sequence diagram shows the interaction between different agents.

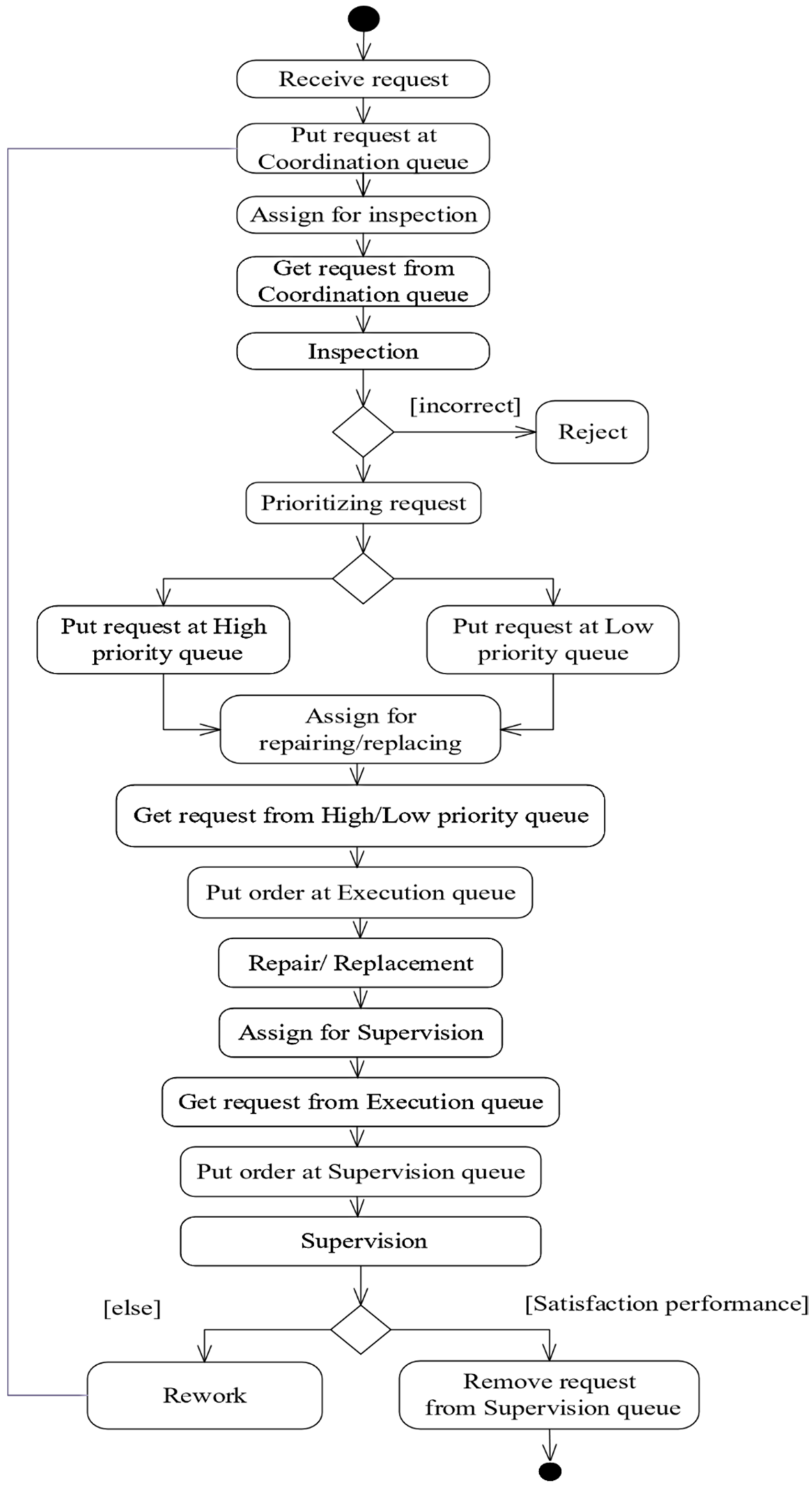


Figure 5-2. Maintenance workflow process.

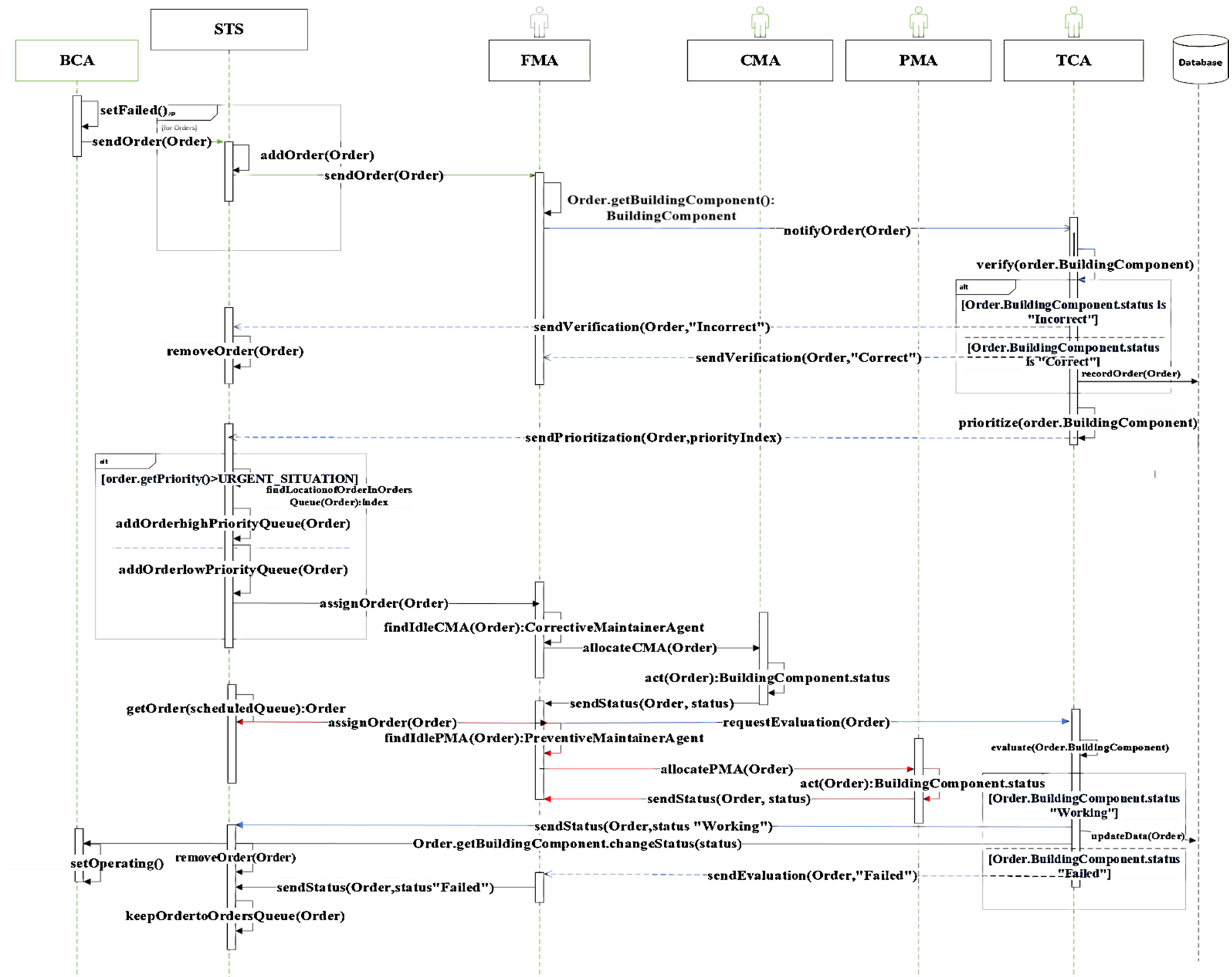


Figure 5-3. MARAS sequence diagram for corrective and preventive maintenance orders.

5.2.2.2 Workflow process abstraction

The abstraction phase facilitates the transition from the definition to the simulation phase. In the abstraction phase, the workflow process is abstracted into a discrete event model. In this phase, the maintenance workflow process is simulated as a process with a discrete sequence of operations. To simulate workflow process, important sequences and events are modeled with low levels of abstraction of the component details. Discrete events include queues, decisions, services, and resource pools. The workflow process model updates the status of orders in different maintenance queues, namely coordination, high priority, low priority, scheduled, execution, and supervision queues (Section 5.3.1). The process commences once an order is registered to the system, and continues until the order has been completed and its status is marked “closed”.

5.2.3 Modeling MARAS (Phase 6)

MARAS as a simulation-based system provides the opportunity for facility managers to simulate resource allocation plans based on received maintenance reports. Developing such a system encompasses 2 phases, which are modeling building component agent’s behavior and modeling resource agent’s behavior. In general, mechanical BCAs have similar behaviors including: operating, failed, repair, and replacement. While human resources have different behaviors that depend on their role in the maintenance management process. Each of which is described in Table 5-2. In order to develop MARAS, the behavioral and interactive characteristics of each agent are abstracted.

BCAs are the different components of a building (e.g., elevator and HVAC). This study focuses on modeling the operation, repair, and maintenance of elevators in hospitals (Section 5.3.2). As explained in Section 4.2.2.1, human resources and building components are defined as agents. Along the workflow process, human resource agents play their roles according to their assigned responsibilities. According to the literature, conventionally facility managers pursue two types of maintenance strategies; preventive and corrective. Therefore, human resource agents include PMA, CMA, FMA, and TCA. CMAs and PMAs undertake corrective maintenance and preventive maintenance actions on scheduled basis, respectively.

Agents interact with each other in the context of the workflow framework. In registration, an order (from failed BCA) is added to the coordination queue. Then in the planning and resource allocation level, FMA receives the order and notifies TCA to verify its correctness. If the order is accepted, TCA checks the order priority degree and place it in the high or low priority queue. Subsequently, the available resources are allocated to the order by FMA. At the execution level, the CMA moves to the BCA and places the order in the execution queue. After completing the order, it is placed in the supervision queue. At the supervision and documentation level, if the TCA confirms the quality of the execution, the order will be removed from the supervision queue, otherwise, the order is placed in the failing queue for rework. Else, TCA removes the order from the supervision queue. In the concluding step, a detailed report is issued for documentation.

Whereas the maintenance activities are repetitive, agents should follow set up rules. As shown in Table 5-2 human resource agents are allocated to each level of the workflow process (Phase 1).

Table 5-2. Rules for modeling the behaviors of BCAs and resource agents in MARAS.

MAS structural levels	Agent/ System	Rules for describing agent behaviors	Agent's goals
Registration	Workflow process model	• Add or remove order in the coordination queue • Add or remove order in the failing queue • Add or remove order in the high priority queue • Add or remove order in the low priority queue • Add or remove order in the scheduled queue • Add or remove order in the execution queue • Add or remove order in the supervision queue	Arrange orders in different queues, Update schedule
	BCA	• Operating • Failed • Repair • Replacement	Operating continuously with minimum disruption time
Planning and Resource Allocation	FMA	• Assign order to available TCA • Assign accepted order to available CMA	Coordinating the resources to reduce the operation time, Meeting maintenance needs on time
	TCA	• Check coordination queue • Inspecting (Check order validity: correct or incorrect) • Continuing or add order to failing queue • Evaluating (Check order priority: high or low) • Add or remove order in the high priority queue • Add or remove order in the low priority queue • Add or remove order in the scheduled queue • Report preparing	Inspecting, evaluating the requested order
Execution	CMA	• Check high priority queue • Add order to the execution queue • Move to BCA • Get order from the execution queue • Working (repairing, or replacing) • Add order to supervision queue • Check low priority queue) • Working (repairing, or replacing) • Add order to supervision queue • Moving back to FM office	Responding to an unexpected failure of BCA and corrective maintenance

	PMA	• Check scheduled queue • Add to the execution queue • Moving to BCA • Get order from the execution queue • Check BCA based on a predetermined maintenance schedule • Add order to supervision queue • Moving back to FM office	Responding to preventive maintenance of BCA
Supervision	TCA	• Remove order from supervision queue • Supervising the quality of execution • Add order to accepted queue	Supervising the quality of execution

5.2.4 Modeling Simulation-Based Optimization (SBO) (Phase 7)

In the last phase, the collected data is input to the simulation model then the simulation is run. Finally, the developed simulation model is validated by creating a sensitivity analysis experiment, which will be explained more in detail in the result and discussion section later. Furthermore, various resource compositions are tested by applying SBO to generate a near-optimal schedule. By applying the sensitivity analysis, the positive and negative effects of changes are evaluated on the project objectives. It is worthy to mention that; the developed simulation model enables facility managers to test different resource allocation scenarios in a virtual laboratory. Simulations have been developed to create a baseline model for calibration and comparison of results. Through a real-world case study, the developed simulation model is further explained and its applicability and benefits are demonstrated.

In this research, a SBO method is used to improve FM decision-making regarding optimum resource allocation. Anylogic is used for the simulation part. OptQuest is used for the optimization part, which is compatible with Anylogic. OptQuest provides a potential solution to the model developed in the Anylogic software. In this section, resource allocation optimization is performed to find the optimum number of resources while using the objective function to minimize the mean annual down-time of the building components (e.g., elevators). To fulfill this objective, OptQuest is used as a SBO engine.

As explained in Section 3.8, the SBO process is implemented by generating the initial population of size N in the initial generation. The optimization phase has the following steps as shown in

Figure 5-4 (1) the facility management sets the number of generations (*G*) and the population size *(P)*. (2) Then, the initial population is generated randomly for the first simulation (3). MARAS implements a simulation tool to compute the $\mu_{t_{rr}}$, $\mu_{t_{re}}$, $\mu_{t_{ma}}$, and $\mu_{t_{ch}}$ for each scenario (4). The input factors to the optimization engine are explained in Table 5-3. This process is repeated for all scenarios in the generation (5 and 6). The optimization engine evaluates the fitness of the objective function for each scenario based on the values in each simulation run (7) and checks whether the objective function value is better than the previous ones or not (9). If necessary, it adds a new best result and a new set of values to evaluation (10). The constraint is applied to specify the boundaries of values as explained in equation 6 (8). The termination condition is assessed in this phase (11). Subsequently, the SS and TS operations are applied to the entire population (12). This procedure is iteratively repeated for all members in all generations until the termination criteria is reached (13). The results of the optimization are shown in the form of convergence graph, which will be utilized to inform facility management of different scenarios, as well as the trade-off relationships among the various scenarios (14).

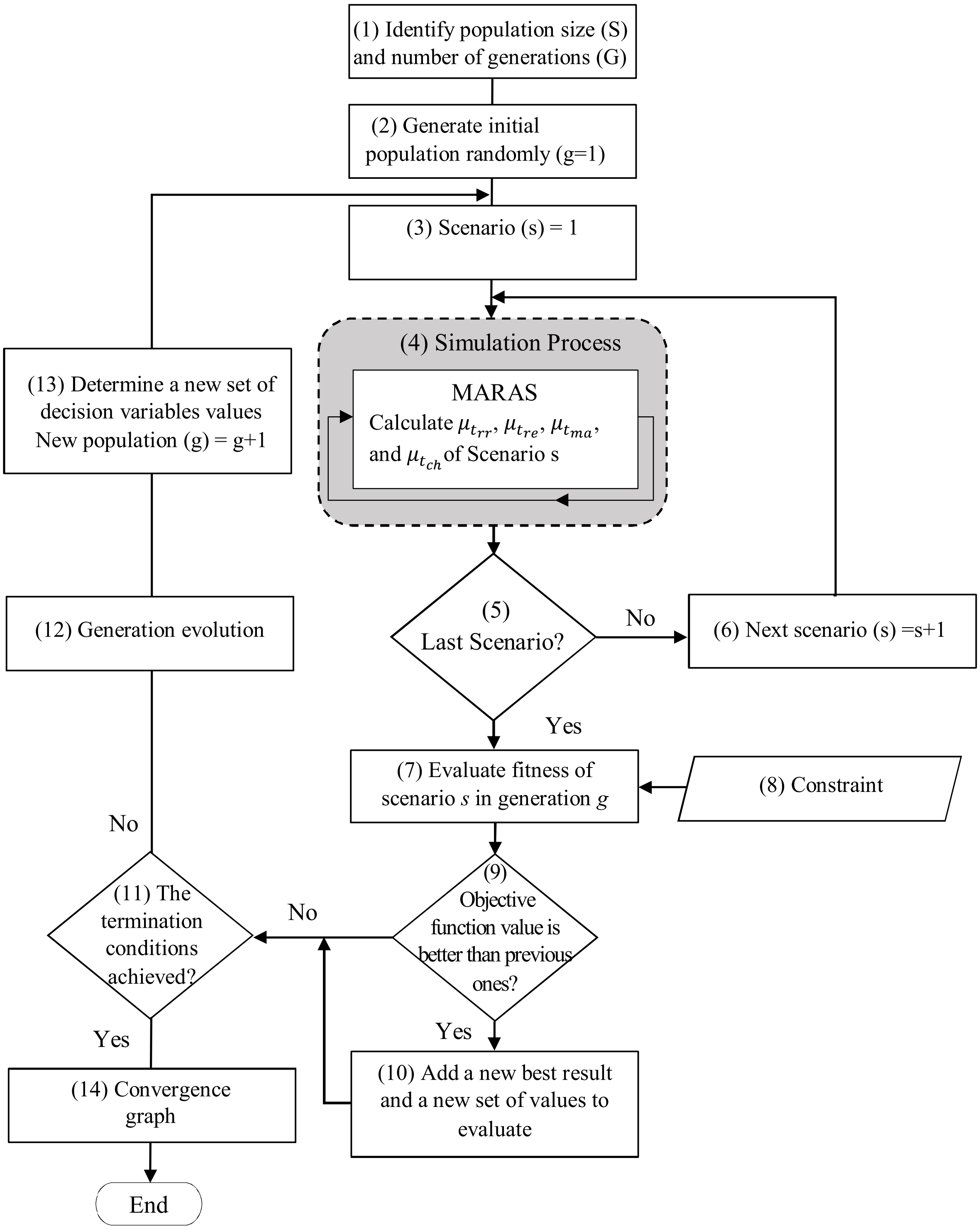


Figure 5-4. SBO process using OptQuest and Anylogic.

Setting up the objective function, decision variables, and constraints:

In order to calculate the down-time of building components, four different times, including mean repair time ($\mu_{t_{rr}}$), mean replacing time ($\mu_{t_{re}}$), mean maintenance time ($\mu_{t_{ma}}$), and mean checking time ($\mu_{t_{ch}}$) are calculated separately by equations (1), (2), (3), and (4). Then, these parameters are added to each other as shown in equation (5).

1) The mean repair time is calculated based on the mean number of BCAs in the ‘Repair” state in one year and “Repair Time” and “CMA Number” parameters, shown in equation (1).

$$\mu_{t_{rr}} = \mu_{BCA}^{rr} * (t_{rr} / n_{CMA}) \quad (1)$$

where,

$\mu_{t_{rr}}$ is the mean repair time,

μ_{BCA}^{rr} is the mean number of BCAs in the “Repair” state,

t_{rr} is the repair time,

n_{CMA} is the number of CMA,

2) The mean replacing time is calculated based on the mean number of BCAs in the “Replacement” state in one year and “Replace Time” and “CMA Number” parameters, shown in equation (2).

$$\mu_{t_{re}} = \mu_{BCA}^{re} *(t_{re} / n_{CMA}) \quad (2)$$

where,

$\mu_{t_{re}}$ is the mean replacing time,

μ_{BCA}^{re} is the mean number of BCAs in the “Replacement” state,

t_{re} is the replacing time,

n_{CMA} is the number of CMA,

3) The mean maintenance time is calculated based on the mean number of BCAs in the "Maintenance Checkup" state in one year and "Maintenance Time" and "PMA Number" parameters, shown in equation (3).

$$\mu_{t_{ma}} = \mu_{BCA}^{mc} * (t_{ma} / n_{PMA}) \quad (3)$$

where,

$\mu_{t_{ma}}$ is the mean maintenance time,

μ_{BCA}^{mc} is the mean number of BCAs in the "MaintenanceCheckup" state,

t_{ma} is the maintenance time,

n_{PMA} is the number of PMA,

4) The mean checking time is calculated based on the mean number of BCAs in the "Failed" state in one year and "Checking Time" and "TCA Number" parameters, shown in equation (4).

$$\mu_{t_{ch}} = \mu_{BCA}^{fa} * (t_{ch} / n_{TCA}) \quad (4)$$

where,

$\mu_{t_{ch}}$ is the mean checking time,

μ_{BCA}^{fa} is the mean number of BCAs in the "Failed" state,

t_{ch} is the checking time,

n_{TCA} is the number of TCA,

μ_{BCA}^{rr}, μ_{BCA}^{re}, μ_{BCA}^{mc}, and μ_{BCA}^{fa} are calculated by MARAS model and used as input to the optimization experiment.

The objective function of the optimization model is to minimize the mean annual down-time of the elevators in the MARAS, which includes $\mu_{t_{rr}}$, $\mu_{t_{re}}$, $\mu_{t_{ma}}$, and $\mu_{t_{ch}}$. Mathematically, the objective function is to minimize ($\mu_{t_{rr}}$+ $\mu_{t_{re}}$+ $\mu_{t_{ma}}$+ $\mu_{t_{ch}}$) as shown in equation (5).

Objective function Min $z = (\mu_{BCA}^{rr} * (t_{rr}/n_{CMA})) + (\mu_{BCA}^{re} * (t_{re}/n_{CMA})) + (\mu_{BCA}^{mc} * (t_{ma}/n_{PMA})) + (\mu_{BCA}^{fa} * (t_{ch}/n_{TCA}))$ (5)

where,

z is the mean annual down-time of BCAs,

μ is mean value, n is number of agent, rr is repair, re is replacement, mc is maintenance checkup, and fa is failed. As shown in Table 5-3, the decision variables are n_{CMA}, n_{PMA}, and n_{TCA}. Some parameters (i.e., t_{rr}, t_{re}, t_{ma}, and t_{ch}) are remain steady at 2 (hours), 4 (hours), 2 (hours), and 3 (hours).

As explained in Section 2.2.2, the availability of building components is very important in hospitals. Elevators' availability plays an important role in the operation and maintenance of hospitals (Salah et al. 2018). Therefore, it is essential that elevators are available for use and operation. According to data collected from the survey, interviews, and the case study, the constraints are assumed as follows:

1- To the author's knowledge, that there is no specific standard for the minimum acceptable percentage of elevators availability in hospitals.

2- According to the conducted interview with the facility management team at the Madar hospital, which represents the owner's requirements, 80% availability is set as the minimum acceptable value in this study. Therefore, it is assumed that the average availability of elevators to be not less than 80% per year as shown in equation (6).

$$80\% \le \frac{\sum_{i=1}^{365}(\frac{n_i}{n})}{365} \quad (6)$$

where,

i is days, n_i number of elevators in operation on the ith day, n is total number of elevators.

3- The number of resources is another type of constraint in this optimization as shown in equations (7), (8), and (9). Values are defined according to the project specifications.

$1 \le n_{CMA} \le 5$, *where,* n_{CMA} is the number of CMA, (7)

$1 \leq n_{PMA} \leq 2$, *where,* n_{PMA} is the number of PMA, (8)

$1 \leq n_{TCA} \leq 5$, *where,* n_{TCA} is the number of TCA, (9)

The objective function (Equation 5) is a cumulative function over the planning horizon while the constraint in Equation 6 corresponds to each period of time. Equation 5 optimizes the annual mean down-time for elevators, while the constraint defines the acceptable threshold for elevators availability. Appendix G shows the optimization experiment in Anylogic.

Table 5-3. Set up the solution space.

Parameters and variables		**Type**	**Value**		
			Min	**Max**	**Step**
Fixed parameters	t_{rr}	hour	2	-	-
	t_{re}	hour	4	-	-
	t_{ma}	hour	2	-	-
	t_{ch}	hour	3	-	-
Decision variables	n_{CMA}	integer	1	5	1
	n_{PMA}	integer	1	2	1
	n_{TCA}	integer	1	5	1

The simulation model generates the objective function value. Figure 5-5 shows that how OptQuest interacts with agents (i.e., BCAs, CMAs, PMAs, and TCAs) in simulation model. Mean repair time, mean replacing time, mean maintenance time, and mean checking time are calculated through the simulation, which is coupled with optimization. In SBO model, the simulation engine is responsible for calculating the parameters and sending the results to the optimizer for evaluation. It shall be mentioned that there are fixed parameters such as repair time, replacement time, maintenance time, and checking time. The decision variables are CMAs, PMAs and TCAs, which are changed at each simulation run as well as the mean number of BCAs in the 'Repair" state of BCAs, the mean number of BCAs in the "Replacement' state, the mean number of BCAs in the "MaintenaceCheckup" state, and the mean number of BCAs in the "Failed' state of BCAs.

$\mu_{t_{rr}} = \mu_{BCA}^{rr} * (t_{rr} / n_{CMA})$		
$\mu_{t_{rr}}$	mean repair time	?
μ_{BCA}^{rr}	mean number of BCAs in the "Repair" state	statsCoRepair
t_{rr}	repair time	RepairTime
n_{CMA}	number of CMA	cMAgents [..]
$\mu_{t_{re}} = \mu_{BCA}^{re} * (t_{re} / n_{CMA})$		
$\mu_{t_{re}}$	mean replacing time	?
μ_{BCA}^{re}	mean number of BCAs in the "Replacement" state	statsCoReplacement
t_{re}	replacing time	ReplacementTime
n_{CMA}	number of CMA	cMAgents [..]
$\mu_{t_{ma}} = \mu_{BCA}^{mc} * (t_{ma} / n_{PMA})$		
$\mu_{t_{ma}}$	mean maintenance time	?
μ_{BCA}^{mc}	mean number of BCAs in the "MaintenanceCheckup" state	statsCoMaintenanceCheckup
t_{ma}	maintenance time	MaintenanceTime
n_{PMA}	number of PMA	pMAgents [..]
$\mu_{t_{ch}} = \mu_{BCA}^{fa} * (t_{ch} / n_{TCA})$		
$\mu_{t_{ch}}$	mean checking time	?
μ_{BCA}^{fa}	mean number of BCAs in the "Failed" state	statsCoFailed
t_{ch}	checking time	CheckingTime
n_{TCA}	number of TCA	tCAgents [..]

Figure 5-5. The objective function value is calculated by simulation model

5.3 Implementation and Case Study

Among various simulation software, Anylogic 7.3.4 (XJ Technologies 2014) has been selected as the simulation platform for development of simulation models. Anylogic has ABM, DES, and SD platforms and is able to combine these simulation methods simultaneously. Therefore, Anylogic is selected for integrating DES and ABM to simulate MARAS and workflow process model.

5.3.1 Simulating Workflow Process with DES

The workflow process model is implemented in Anylogic 7.3.4 (XJ Technologies 2014), a Java-based DES platform (Figure 5-6) according to the procedure which is described in Phase 5. Table 5-4 demonstrates Anylogic elements used in the implementation of workflow process.

Table 5-4. Anylogic elements used to model workflow process with DES.

Element	Symbol	Description
Dynamic Variable		Dynamic variable (SD library).
Source		Generates agents.
Sink		Ends the process.
Delay		Delays agents for a given amount of time.
Queue		A queue of agents waiting to be accepted by the next block.
Select Output		Routes the input agents to one of the two output ports according to condition.
Resource Pool		Defines a set of resource unis.
Seize		Seizes resources units from the given ResourcePool block.
Release		Releases resources units that was seized by seize object.
Time Measure Star		Measures the time that agents spend between two objects.
Time Measure End		

The source block “NewOrderAdmission” generates new orders at the rate defined by “OrderAdmissionPerDay” which is a dynamic variable. The “NewOrderAdmission” is defined by inter arrival time. According to the survey results, the inter-arrival time between orders is randomly distributed. Reviewing the literature reveals that exponential distribution is often used for the modeling of time between events. On analyzing the answers of the participants in the survey, it is assumed that the entry of the order into the simulation model follows an exponential distribution with a mean of 2 hours. The system re-evaluates this dynamic variable after each new order generation. After registration, incoming orders are added to the coordination queue, and TCA is sized for performing the inspection. If the order is accepted, it enters the execution queue, otherwise, it will be deleted from the system. Afterward, CMA is seized for repair or replacement of the failed building components. Executed orders are sent to the supervision queue for supervision on the quality of performance. At this level, TCA is sized for supervising. Finally, the executed order is removed from the supervision queue, otherwise, it will be returned to the coordination queue as shown in Figure 5-6. PMAs have a separate sub-process to execute routine maintenance practices. The developed DES allows the facility manager to measure the time it takes for each order to pass through the workflow process.

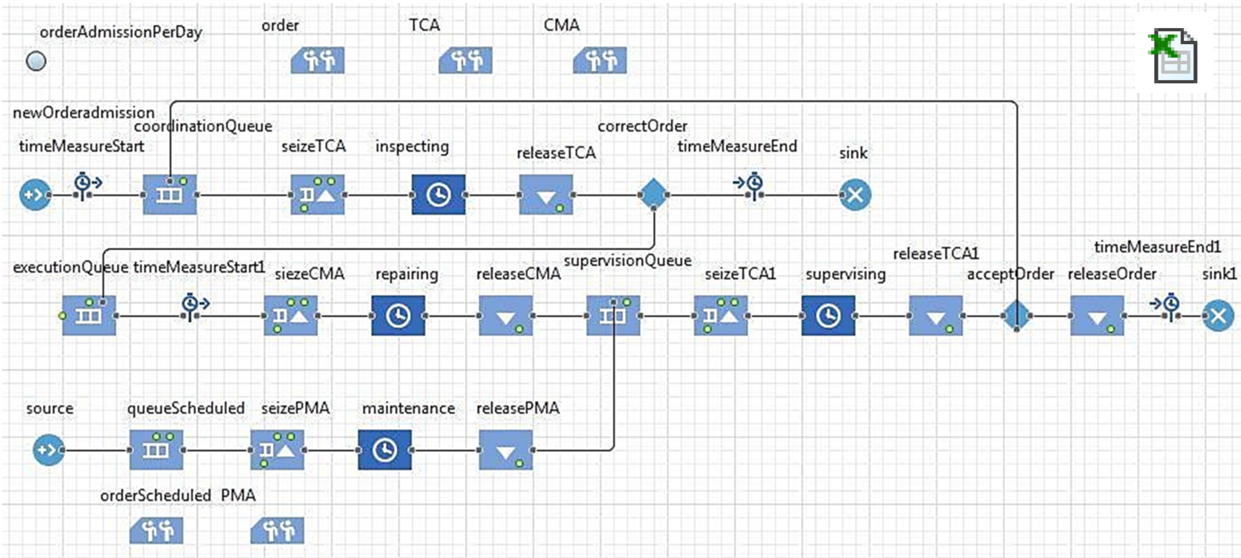


Figure 5-6. Simulation of the workflow process.

The case study data is used as input to DES model. This data includes the number of resources (ResourcePool), order time intervals, and service times. The number of resources is assumed to be discrete as shown in Table 5-5. As mentioned earlier, it is assumed that the order interval is distributed exponentially, with a mean of two hours. Service times for inspection, repair, supervising, and maintenance are assumed distributed following a triangular distribution of time units (min, mode and maximum). Number of orders and the time of their entry into the DES model is based on data taken from the Excel file of Madar hospital.

DES model output measures number of orders in different queues including coordination queue, execution queue, supervision queue, and scheduled queue in real-time. A sample of output data has been shown in Figure 5-13.

Table 5-5. Input data to the DES model

Resource Pool (unit) 			Service time distribution (minutes) 			
TCA	CMA	PMA	Inspecting	Repairing	Supervising	Maintenance
Uniform (1,5)	Uniform (1,5)	Uniform (1,3)	Triangular (15,20,30)	Triangular (30,60,180)	Triangular (60,90,120)	Triangular (20,45,60)

5.3.2 Simulating MARAS (Resource Allocation) with ABM

5.3.2.1 Main Class

MARAS is also simulated by applying the ABM method in Anylogic 7.3.4 (X Technologies 2014), a Java-based ABM platform. Table 5-6 demonstrates Anylogic elements used in the implementation of MARAS. In order to implement MARAS, the structure of the main class and the four agent classes are defined in Anylogic.

The main class in Anylogic represents the simulation engine. This class is responsible for integrating all components of the model, controlling the interaction between agents and their environment, performing simulations, and producing results. The tasks of the main class include setting up the hospital building environment, creating a population of agents, managing the agent queue, controlling the performance of the model, and generating results.

The environment of the selected hospital is created using engineering drawings in Anylogic. Section 5.3.4 describes the simulation of the hospital environment in more detail. The agent populations in the main class are defined using the elements listed in

Table 5-7. These elements create the agent populations and set the initial location of the agents in the case study.

Table 5-6. Anylogic elements used to model MARAS with ABM.

Element	**Symbol**
Agent population	
Parameter	
Function	
Collection (linked list)	

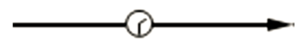
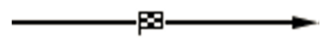
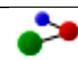
Variable	
Event (scheduled function)	
Statistics	
Data set	
Excel file	
TCA	
PMA	
CMA	
FMA	
Time-triggered transition	
Message-triggered transition	
State-end-triggered transition	
Link to agents	
Link to main class	

Table 5-7. Agent populations' elements in MARAS.

Element	Purpose
buildingComponents [..]	Represents the created population of BCAs
cMAgents [..]	Represents the created population of CMAs
pMAgents [..]	Represents the created population of PMAs
tCAgents [..]	Represents the created population of TCAs
setUpLocations	Sets up the initial location of agents in the building

The next step in building MARAS is to define different queues and functions. These functions integrate workflow with the resource allocation process. Collections and functions in the main class are shown in Table 5-8. Collections are used to store orders in the queues and functions are used to add or remove orders from the queues. Queues must be organized based on the FIFO principle. In the following section, agents are defined by their behaviors and their interactions.

Table 5-8. Agent queues' elements in MARAS.

Element	Purpose
coordinationRequest	Store orders in the coordination queue
highPriorityRequest	Store orders in the high piority queue
lowPriorityRequest	Store orders in the low piority queue
scheduledRequest	Store orders in the scheduled queue
executionRequest	Store orders in the execution queue
supervisionRequest	Store orders in the supervision queue
failingRequest	Store orders in the failing queue
putRequest_coordinationQueue	Add orders to the coordination queue
getRequest_coordinationQueue	Receive orders from the coordination queue
deleteFromCoordinationQueue	Remove orders from the coordination queue
putRequest_highPriorityQueue	Add orders to the high priority queue
getRequest_highPriorityQueue	Receive orders from the high priority queue
deleteFromhighPriorityQueue	Remove orders from the high priority queue
putRequest_lowPriorityQueue	Add orders to the low priority queue
getRequest_lowPriorityQueue	Receive orders from the low priority queue
deleteFromlowPriorityQueue	Remove orders from the low priority queue
putRequest_scheduleQueue	Add orders to the schedule queue
getRequest_scheduleQueue	Receive orders from the schedule queue
deleteFromscheduleQueue	Remove orders from the schedule queue
putRequest_executionQueue	Add orders to the execution queue

getRequest_executionQueue	Receive orders from the execution queue
deleteFromexecutionQueue	Remove orders from the execution queue
putRequest_supervisionQueue	Add orders to the supervision queue
getRequest_supervisionQueue	Receive orders from the supervision queue
deleteFromSupervisionQueue	Remove orders from the supervision queue
putRequest_failingQueue	Add orders to the failing queue
deleteFromFailingQueue	Remove orders from the failing queue

The main class is also responsible for updating the agents' population, preventive maintenance schedule, calculating the availability of building components, gathering statics related to human resources utilization, and updating the databases linked to the model. Table 5-9 shows the elements used to perform simulation analysis in Section 5.4.1.

Table 5-9. Results and analysis elements in MARAS.

Element	**Purpose**
updateOnJan	Update BCAs and resources every January
Gather statistics on the average time spent by BCAs in each state during simulation	
statsCoOperating	Calculate the number of BCAs in Operating state
statsCoFailed	Calculate the average number of BCAs in Failed state
statsCoRepair	Calculate the average number of BCAs in Repair state
statsCoReplacement	Calculate the average number of BCAs in Replacement state
statsCoMaintenanceCheckup	Calculate the average number of BCAs in Maintenance state

availabilityStatistics	Calculate the average availability of a BCA in a year
Gather statistics on the average time spent by TCAs in each state of maintenance activity during simulation time	
statsTCAIdle	Calculate the average time spent by the TCA on "Idle in office" in one year
statsTCAMoving	Calculate the average time spent by the TCA on " Moving" in one year
statsTCAInspecting	Calculate the average time spent by the TCA on " Inspecting " in one year
statsTCAReportPreparing	Calculate the average time spent by the TCA on " Report preparing " in one year
Gather statistics on the average time spent by CMAs in each state during simulation time	
statsCMAIdleInOffice	Calculate the average time spent by the CMA on "Idle in office" in one year
statsCMACheckingHPR	Calculate the average time spent by the CMA on “Checking HPR” in one year
statsCMACheckingLPR	Calculate the average time spent by the CMA on “Checking LPR” in one year
statsCMAMovingToBCAHPR statsCMAMovingToBCALPR	Calculate the average time spent by the CMA on “Moving to BCA with HPR and LPR” in one year
statsCMAWorkingOnHPR	Calculate the average time spent by the CMA on “Working on BCA with HPR” in one year
statsCMAWorkingOnLPR	Calculate the average time spent by the CMA on “Working on BCA with LPR” in one year
statsCMAMovingToOffice	Calculate the average time spent by the CMA on “Moving to office” in one year
Gather statistics on the average time spent by PMAs in each state during simulation	

statsPMAIdleInOffice	Calculate the average time spent by the PMA on "Idle in office" in one year
statsPMAMovingToBC	Calculate the average time spent by the PMA on " Moving to BCA " in one year
statsPMAMovingToOffice	Calculate the average time spent by the PMA on " Moving to office " in one year
statsACheck	Calculate the average time spent by the PMA on performing “A check " in one year
statsBCheck	Calculate the average time spent by the PMA on performing “B check " in one year
statsCCheck	Calculate the average time spent by the PMA on performing “C check " in one year
statsServiceCrewSize	Calculate the population of resource agents
CoOperatingSet CoFailedSet CoRepairSet CoReplacementSet CoMaintenanceSet	Create data sets for the average time spent in states obtained by the BCA’s statistics
TCAsIdleSet TCAsMovingSet TCAsInspectingSet TCAsReportingSet	Create data sets for the average time spent in states obtained by the TCA’s statistics
CMAsIdleInOfficeSet CMAsCheckingHPRSet	Create data sets for the average time spent in states obtained by the CMA’s statistics

CMAsMovingToBCAHPR CMAsCheckingLPRSet CMAsWorkingOnHPRSet CMAsMovingToBCALPRSet CMAsMovingToOfficeSet CMAsWorkingOnLPRSet	
PMAsIdleInOfficeSet PMAsMovingToBCASet PMAsMovingToOfficeSet ACheckSet BCheckSet CCheckSet	Create data sets for the average time spent in states obtained by the PMA's statistics
BCAsExcel	Update the Excel file with statistics related to the utilization of BCAs
TCAsExcel	Update the Excel file with statistics related to the utilization of TCAs
CMAsExcel	Update the Excel file with statistics related to the utilization of CMAs
PMAsExcel	Update the Excel file with statistics related to the utilization of PMAs

5.3.2.2 Agent Classes

In addition to the main class, MARAS has four classes that represent the building components and human resources involved in maintenance operations. Each of these classes contains a state chart with the elements needed for the operation. Each agent class is discussed separately as follows:

The Elevator Agent

According to conducted survey results, more than 30% of work orders within a year are related to repair and preventive maintenance of the elevators in typical hospital buildings. In addition, 60% of the survey participants stated that the elevator has a high RPN value that must be worked on first. Conducting a survey, a review of the literature and media reports (as explained in Section 2.2.2) highlights concerns about elevator failure in hospitals. Therefore, in this study, the maintenance of service elevators has been investigated in the case study.

According to the procedure, which is described in Phase 6 building component agent's behaviors are modeled and implemented in Anylogic 7.3.4. As shown in Figure 5-7, the Operating state of the elevator has two Boolean types of behavior; Busy (true) and Idle (false). Busy state includes elevator car behaviours that result from internal and external user requests. It should be clarified that simulating elevator utilization is beyond the scope of this research. To modeling elevators' maintenance behaviour, several parameters are defined based on the elevator maintenance information, such as the MTBF and "ReplacementNeeded". Order is generated as soon as BCA is failed and added to the coordination queue. The "generatOrder" interaction is a condition interaction as shown in Figure 5-7. Table 5-10, presents the transactions, parameters, variables, and input data in details. As shown in Figure 5-7, after the order generation step, the model advises if failed component should be replaced or repaired. This decision is made by considering several parameters including, service life of the component (age), number of previous repairs, performance of the component, and TCA observation. It shall be mentioned that the first three decision making process are made automated. For example, to decide whether to change elevator components, MARAS considers the age factor for the main elevator components including elevator rope, pulley, door system, control system, motor, and Elec. supply. "Age" Function is defined to calculate the difference between the time of simulation and the last time that the component was replaced

"TimeLastReplacement". For each and every one of the components, if age factor indicates that the time for replacement is reached, system will automatically generate an order to replace.

Each of the main components of the elevator has a specific service life threshold defined in technical catalog of elevators. According to maintenance information listed for elevators used in Madar hospital, the rope, pulley, door system, control system, motor, and Elec. supply should be changed in the range of 15 to 20 years, 15 to 20 years, 10 to 15 years, 20 to 30 years, 20 to 25 years, and 20 to 30 years, respectively.

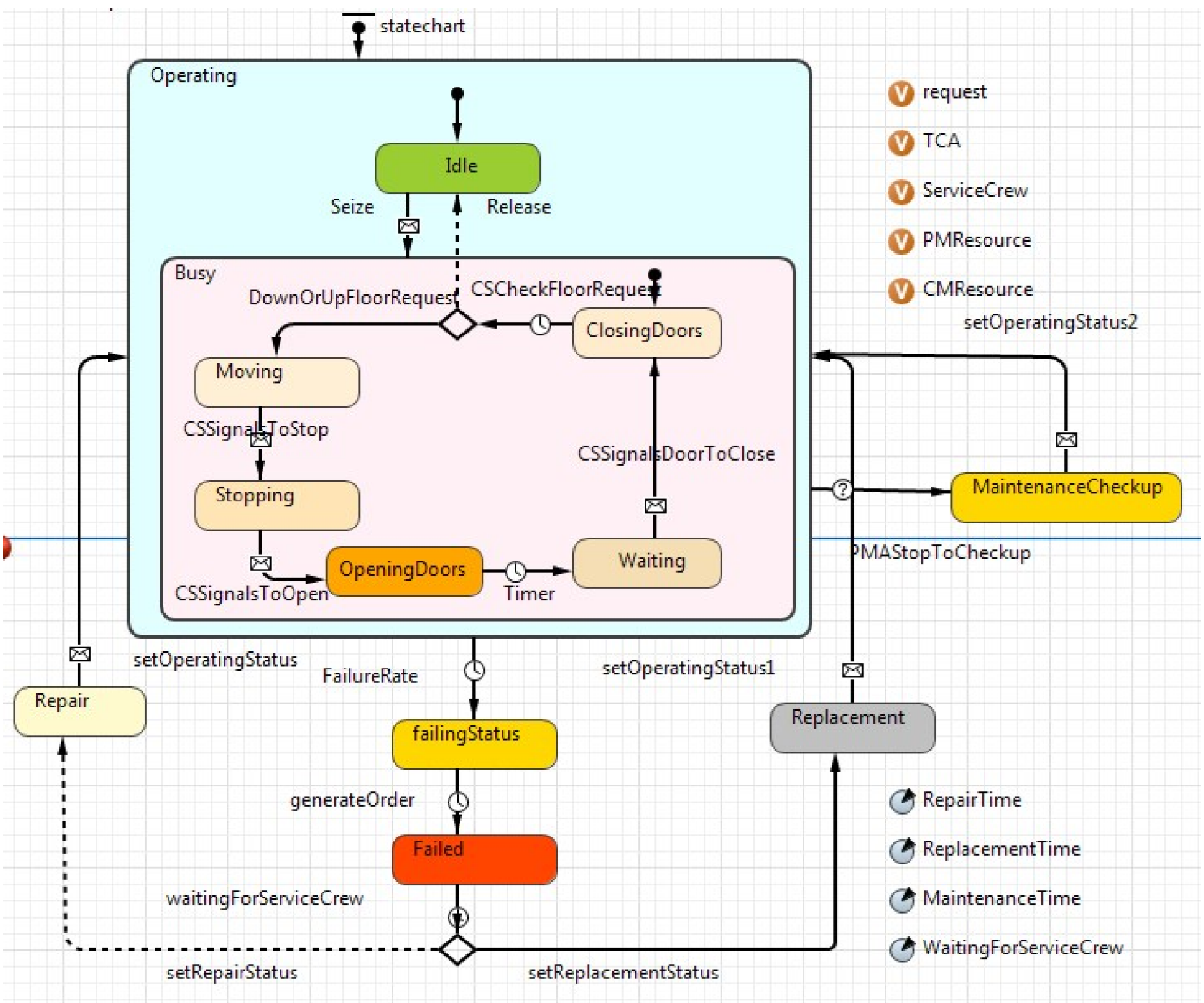


Figure 5-7. Anylogic state chart of BCA (elevator) behavior.

Table 5-10. Adjusted input data in BCAs.

Transition	Triggered by	Assumptions/Action codes (Java)

Failure Rate (MTBF)	Timeout	Timeout: 50 days	

Generate Order	Timeout	// put new order in coordination queue
		Timeout: 1 hours
		`get_Main().putRequest_coordinationQueue(request);`	

`Waiting For ServiceCrew`	Timeout	`WaitingForServiceCrew*triangular(1,2,4) hours`	

`Set Replacement Status`	Condition	// replace the BCA if the TCA has decided to replace or it is time to replace
		`(TCA.replacementNeeded)||`
		`get_Main().TimeForReplacement`
		`request.requestStatus="Replacement"`	

`Set Repair Status`	Message	// repair the BCA `request.requestStatus="Repair"`	
`Set Operating Status`	Message	// the BCA starts operating `request.requestStatus="Operating"`	

`PMA Stop To Checkup`	Condition	// check if the time is for CCkeck or BCheck or ACheck
		`get_Main().annualCheck==true ||`
		`get_Main().semiAnnualCheck==true ||`
		`get_Main().monthlyCheck==true`	

Parameter	**Type**	**Assumptions, Units**	
RepairTime	Timeout	3 hours	
ReplacementTime	Timeout	4 hours	
MaintenanceTime	Timeout	1 hours	
WaitingForServiceCrew	Timeout	2 hours	
Variables	**Type**	**Assumptions, Units**	
replacementNeeded	boolean	false	
TimeForReplacement	Timeout	Cyclic: 20 years	
request	Request	-	
ServiceCrew	Agent	-	
PMResource	Agent	-	
CMResource	Agent	-	
TCA	Agent	-	
Population	**Type**	**Assumptions, Units**	
`BCA population`	Number	10	
`CMA population`	Number	1-5	
`PMA population`	Number	1-3	
`TCA population`	Number	1-5	
Statistics	**Type**	**Expression**	**Condition**
availabilityStatistics	Sum	10/BCAs.size()	item.Operating
downTimeStatistics	Sum	10/BCAs.size()	item.Failed || item.Repair || item.Replacement || item.MaintenanceCheckup

The Team Coordinator Agent

Then, according to the method described in Phase 6, the resource agent's behaviors are modeled and implemented in Anylogic 7.3.4. TCA is responsible for inspecting the generated order in terms of its correctness and its priority degree. TCA is also supervising the quality of BCA operation after the execution is completed. TCA has three main states of "Inspecting", "Evaluating", and "Supervising" as shown in Figure 5-8. TCA checks the coordination queue, if there is an order, the TCA moves for inspection. In the "Inspection" state, if the order is correct, the TCA checks the order priority, otherwise, the order is discarded and added to the failing queue.

To prioritize maintenance orders, two prioritization methods are considered in the simulation model; subjective rating and risk priority number (RPN). Subjective ranking is based on TCA experience and it is accomplished in the evaluation state. Therefore, TCA, as a supervisor, determines the priority level of work orders based on visual inspection and subjective ranking (Figure 5-8). To this purpose, the MARAS model has been developed as an open model allowing for the user to intervene in prioritization as shown in Figure 5-13.

According to Xiao et al. (2011), the RPN method is also used to prioritize failure modes in maintenance activities. This indicator is calculated based on three parameters: probability of occurrence, probability of detection, and potential severity (Wu and Zhao 2014). RPN is calculated by multiplying these numerical values (Sellappan and Palanikumar 2013). This factor is scaled with numbers between 1 and 10. In the MARAS model, simulation model can determine the level of prioritization for each order based on the RPN prepared in the Excel spreadsheet as shown in Table 5-11.

In evaluating state, if the order priority degree is higher than the threshold, TCA assigns an index to the order and adds it to the high priority queue, otherwise, the order is added to the low priority queue. In addition, the order can be added to the scheduled queue. Elements used to build the TCA as shown in Table 5-12.

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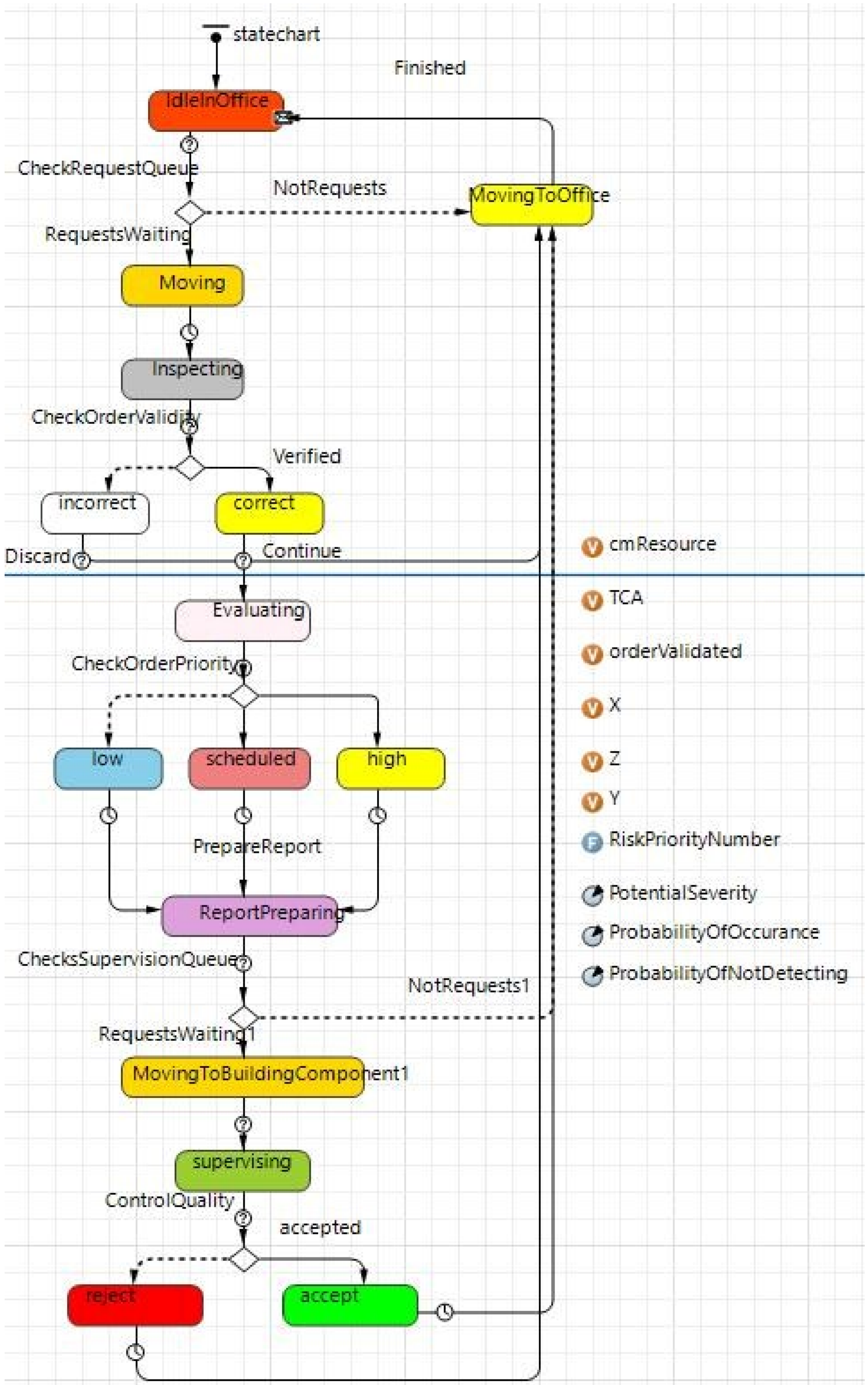


Figure 5-8. Anylogic state chart of TCA behavior.

Table 5-11. RPN of elevator door protection system (Adapted from Wu et al. 2014)

Failure mode	Severity rank	Occurrence rate	Detection rate	RPN	Rank
Safety edges for door	8	0.001	0.015	40	3
Linkage	8	0.001	0.01	40	3
Micro switch	8	0.001	0.008	48	2
Light curtain	8	0.01	0.015	120	1

Table 5-12. TCA class elements in MARAS.

Transition	Triggered by	Assumptions/Action codes (Java)

CheckRequestQueue	Condition	// TCA checks the coordination queue
		Condition:
		`get_Main().getRequest_coordinationQueue()!=null`
		// if it is not empty, TCA gets the order
		Action:
		`request=get_Main().getRequest_coordinationQueue();`

RequestsWaiting	Condition	Condition: `request!=null` Action: `moveTo(10,10);`
movingToBuildingComponent	Timeout	// TCA moves to the BCA Timeout: `MovingTime*triangular(1,2,3) minutes`
CheckOrderValidity	Timeout	// TCA verifies the order validity Timeout : 10-20 (minutes)

Discard	Condition	//TCA reject the order validity
		Condition: `true`
		Action:
		`get_Main().putRequest_failingQueue(request);`

Continue	Timeout	Timeout : 10 (minutes)

CheckOrderPriority	Condition	// TCA prioritizes the order
		Condition: `true`
		Action:
		`get_Main().deleteFromCoordinationQueue(request);`

preparingReport	Timeout	// TCA prepares a report Timeout : 1-2 (hours)

ChecksSupervisionQueue	Message	//TCA checks the supervision queue
		Message : `"CHECK SUPERVISION QUEUE"`
		Action:
		`superVisionRequest=get_Main().getRequest_supervisionQueue();`

RequestsWaiting1	Condition	Condition : `get_Main().orderVisited==true` Action: `moveTo(20,20);`
movingToBuildingComponent1	Timeout	// TCA moves to the BCA Timeout: `MovingTime*triangular(1,2,3) minutes`
ControlQuality	Timeout	// TCA controls the BCA Timeout : 30 (minutes)

`deleteFromSupervisionQueue`	Condition	// TCA deletes to the order from supervision queue
		Condition : `TCA.supervsionStatus == 0`
		Action: `if(request!=null)`
		`{`
		`get_Main().deleteFromSupervisionQueue(superVisionRequest);`
		`get_Main().acceptedRequest.add(acceptedRequest);`
		`}`

Element	**Type**	**Assumptions/Action codes (Java)**
TCA	Agent	-
cmResource	Agent	-
orderValidated	boolean	`true`
X	int	-
Z	int	-
Y	int	-
request	Request	Refers to the orders
MovingTime	Timeout	Timeout: 30 (minutes)
CheckingTime	Timeout	Timeout: 3 (hours)
PotentialSeverity	double	-
ProbabilityOfOccurance	double	-
ProbabilityOfNotDetecting	double	-
RiskPriorityNumber	double	Function body: `return PotentialSeverity* ProbabilityOfOccurance* ProbabilityOfNotDetecting;`

The Corrective Maintenance Agent

Afterward, CMA checks the high priority queue. If there is an order in the queue, it is added to the execution queue, then CMA moves to work, otherwise, the CMA checks the low priority queue. Finally, the order is added to the supervision queue as shown in Figure 5-9. The parameters and decision-making variables and functions are coded to make the agents interact and negotiate with each other. Elements used to build the CMA are shown in Table 5-13.

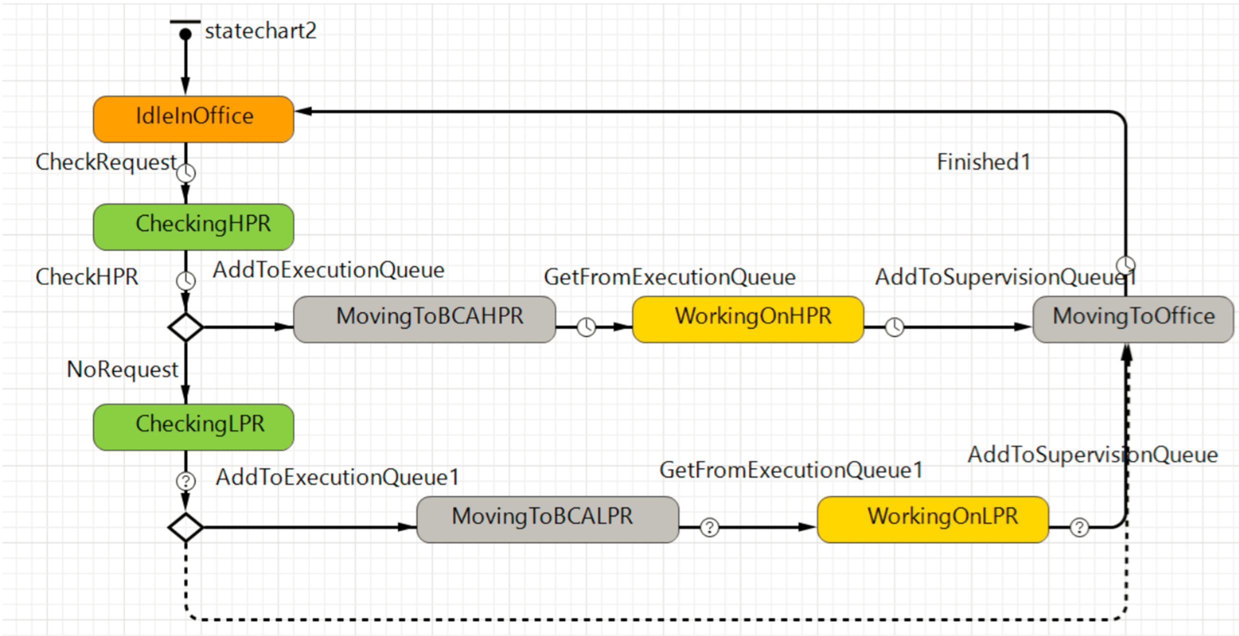


Figure 5-9. Anylogic state chart of CMA behavior.

Table 5-13. CMA class elements in MARAS.

Transition	Triggered by	Assumptions/Action codes (Java)
CheckRequest	Message	// CMA checks the high priority queue

CheckHighPriorityRequest	Timeout	// CMA gets the order from the high priority queue
		Timeout: 10 (minutes)
		Action:
		`request=get_Main().getRequest_highPriorityQueue();`

AddToExecutionQueue	Conditional	// CMA adds the order to the execution queue
		Condition:`request!=null`
		Action:
		`get_Main().putRequest_executionQueue(request);`

NoRequest	Conditional	Condition:`request!=null`
GetFromExecutionQueue	Timeout	// CMA gets the order from the execution queue

		Timeout: 1 (hours) Action:get_Main().getRequest_executionQueue();

AddToSupervisionQueue1	Timeout	// CMA adds the order to the supervision queue
		Timeout : 10 (minutes)
		Action:
		get_Main().putRequest_supervisionQueue(request);
		for(int i=0;i<get_Main().ServiceCrew.size();++i)
		send("CHECK SUPERVISION QUEUE"
		,get_Main().ServiceCrew.get(i));

Finished1	Timeout	Timeout : 10 (minutes) Action: moveTo(this.getX(),this.getY());

CheckLowPriority	Conditional	// CMA checks the low priority queue
		// CMA gets the order from the low priority queue
		Condition:
		get_Main().getRequest_lowPriorityQueue()!=null
		Action:
		request=get_Main().getRequest_lowPriorityQueue()
		;

AddToExecutionQueue1	Conditional	// CMA adds the order to the execution queue
		Condition: request!=null
		Action:
		get_Main().putRequest_executionQueue(request);

GetFromExecutionQueue
1
	Conditional	// CMA gets the order from the execution queue
		Condition:
		get_Main().getRequest_executionQueue()!=null
		Action:
		request=get_Main().getRequest_executionQueue();

AddToSupervisionQueue2	Conditional	// CMA adds the order to the supervision queue
		Condition: true
		Action:
		get_Main().putRequest_supervisionQueue(request);
		for(int i=0;i<get_Main().ServiceCrew.size();++i)
		send("CHECK SUPERVISION QUEUE"
		,get_Main().ServiceCrew.get(i));

Element	**Type**	**Purpose**
request	Request	Refers to the orders

The Preventive Maintenance Agent

To keep the elevator in fair condition, three maintenance checks have been coded based on the elevator's predetermined schedule. According to Elevator Preventative Maintenance report (presented by FM of Madar hospital), the components of the elevator should be inspected monthly for general inspection, every six months for mechanical and electrical issues, and annually for comprehensive inspection. However, maintenance intervals can be adjusted for each BCA in the case study. Figure 5-10 shows the PMA behavior in the form of a state chart. As shown in

Figure 5-10, three Cyclic Events are defined for modeling preventive maintenance intervals, namely monthly checking, semi-annual checking, and annual checking in Anylogic. The scheduled queue is populated by these Events and depleted by the PMAs. Therefore, the PMA checks the scheduled queue. If there is a request, PMA moves for inspection and maintenance. The request is added to the execution queue and after each Check, the request is removed from the execution queue and added to the supervision queue. Elevators must be turned off for maintenance check up every month. Maintenance intervals can be adjusted based on the maintenance schedule of each BCA in the case study. Elements used to build the PMA are shown in Table 5-14.

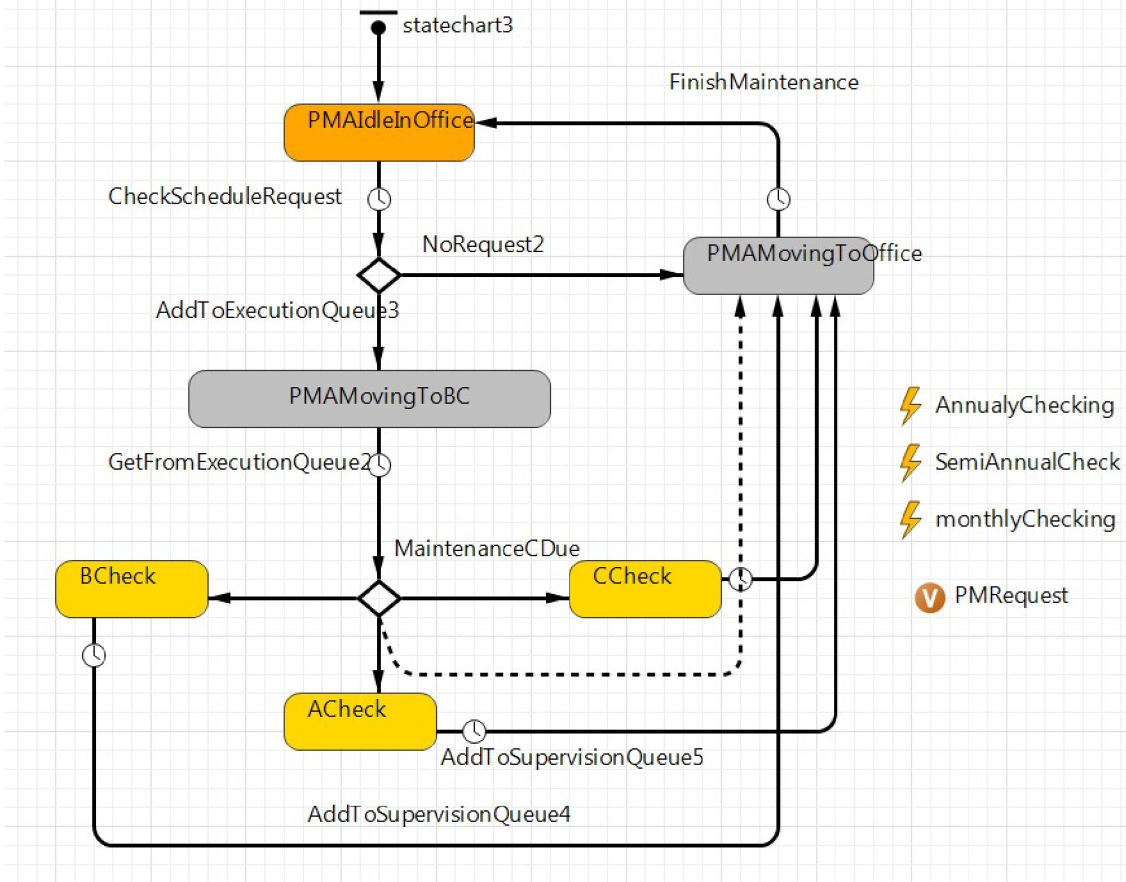


Figure 5-10. Anylogic state chart of PMA behaviour.

Table 5-14. PMA class elements in MARAS.

Transition	Triggered by	Assumptions/Action codes (Java)

CheckScheduleRequest	Message	// PMA checks the scheduled queue
		// PMA gets the order from the scheduled queue
		Message: `"CHECK SECHEDULED QUEUE"`

		Action: PMRequest=get_Main().getRequest_scheduleQueue();

AddToExecutionQueue3	Conditional	// PMA adds order to the execution queue
		Condition: PMRequest!=null
		Action:
		get_Main().deleteFromscheduleQueue(PMRequest);
		get_Main().putRequest_executionQueue(PMRequest);

GetFromExecutionQueue2	Timeout	// PMA gets order to the execution queue Timeout : 10 (minutes) Action: PMRequest=get_Main().getRequest_executionQueue();
AddToSupervisionQueue4	Timeout	// PMA adds order to the supervision queue Timeout : 10 (minutes) Action:get_Main().PeriodMonthlyCheck=false;

Element	Events	Type	Units	Purpose
annualCheck	//CCheck	Timeout	Cyclic: 365 days	Annual maintenance inspection
semiAnnualCheck	//BCheck	Timeout	Cyclic: 180 days	Semi-annual maintenance inspection
monthlyCheck	//ACheck	Timeout	Cyclic: 30 days	Monthly maintenance inspection
PMRequest	-	Request	-	Refers to the maintenance orders

In order to build and analyze the workflow process model and MARAS conveniently, this study makes the following assumptions. Each RA can process only one order at a time, each order must be completed once the operation starts, the occurrence of BCA failure is based on its MTBF, and all the agents are available.

Resource work schedule is considered as one of the inputs of simulation model. The standard working hours for full time resources are 8 hours per day and 5 hours on Saturdays. Figure 5-11 shows the CMAs work schedule at Madar hospital. Consequently, the simulation is performed to show how different agents interact with each other in a dynamic maintenance environment.

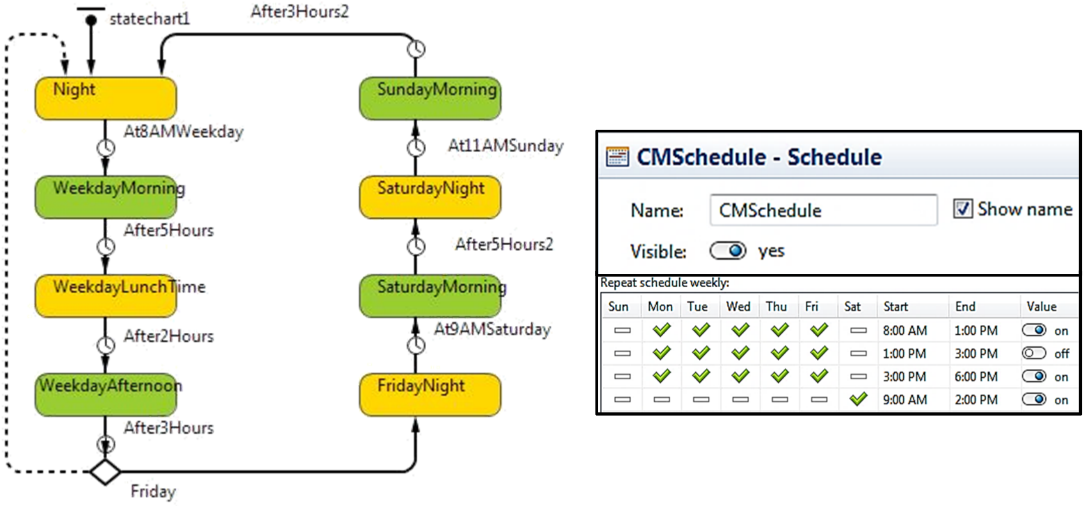


Figure 5-11. Anylogic state chart for resource work schedule.

5.3.3 Interactive Simulation Model

The developed simulation model used "radio controls" features, embedded in Anylogic to become an interactive decision support system. Employing the Controls in MARAS enables the user to execute various scenarios by changing the parameters while the system is running. For instance, "radio controls" are used to perform TCA's action in the system. So, the system enables the TCA to change the Controls state manually based on visual condition assessment and subjective rating. The interactive model enables the facility management team to decide whether to accept or reject, prioritize (put order at high or low or scheduled queue), and replace equipment with an integrated operating system. Figure 5-12 shows the controls, variables, and parameters used for Evaluation, Verification and Supervision states in the TCA state chart. The simulation is performed to elucidate the effect of "radio controls" changes in maintenance queues (results are shown in Figure 5-13). Using the developed simulation model, facility managers are able to monitor and control the number of orders in different maintenance queues. DES has been used to define the input value for each queues.

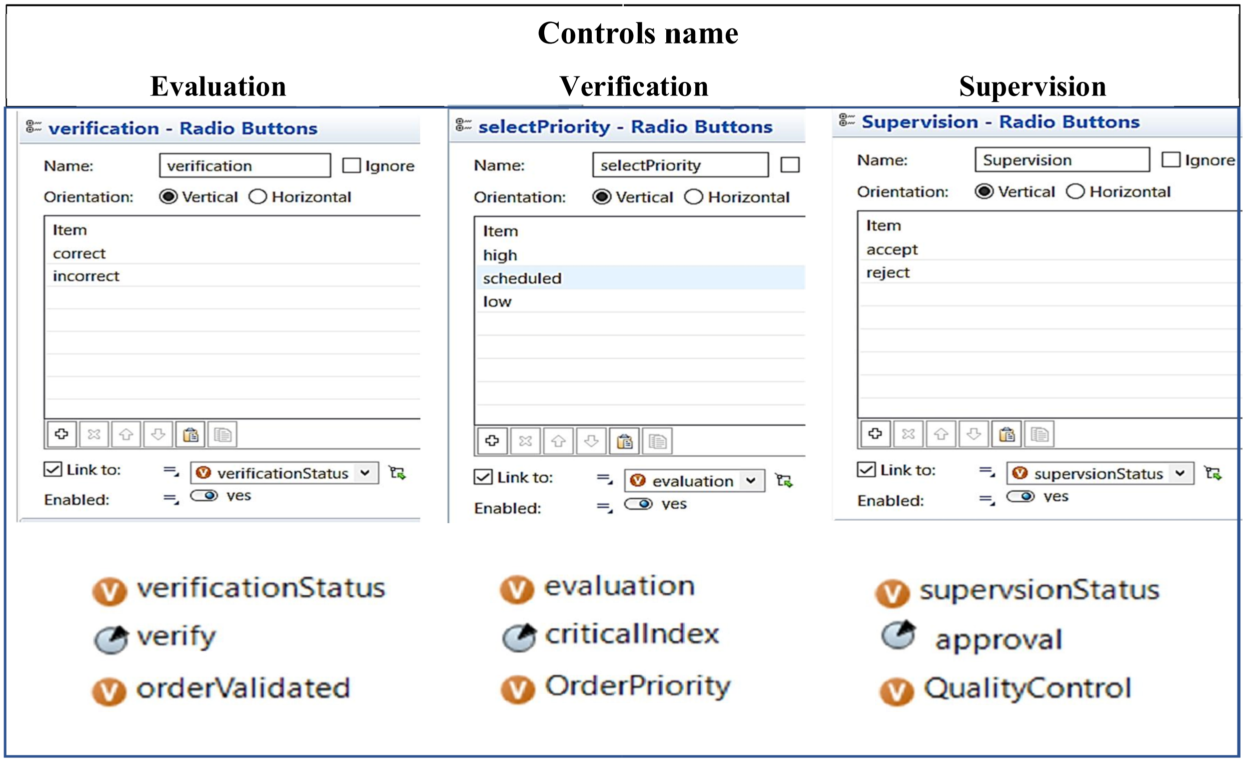


Figure 5-12. Elements used to develop an interactive simulation model.

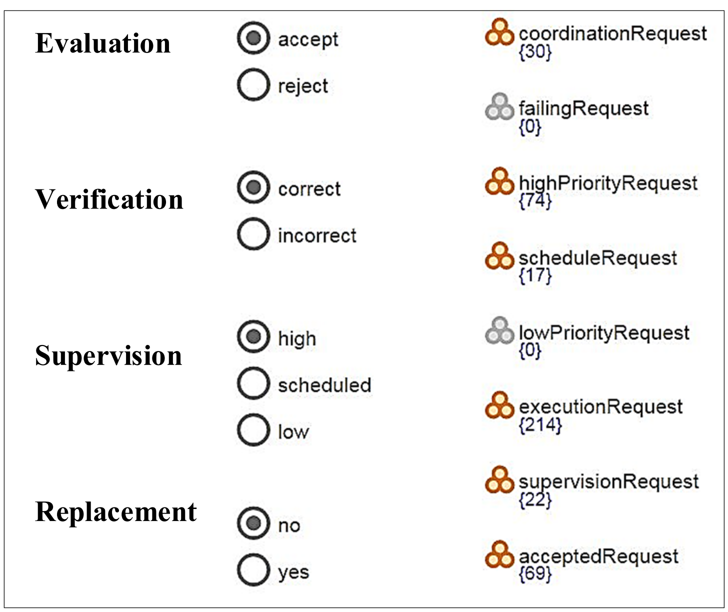


Figure 5-13. Snapshot of interactive simulation model results.

5.3.4 Dynamic 3D Visualization of MARAS

MARAS enables facility managers to improve their decision-making by a better understanding of the building environment in the presence of many components. Accordingly, facility managers can monitor the operation of the huge number of BCAs on different floors of the building. At FM head office, in control room, a facility manager can view the 3D model of the building floors. The purpose of developing a 3D visualization is to assist facility manager in monitoring performance, breakdown, and repair of high priority components in the building. Therefore, facility managers can track operation of building components. Furthermore, facility manager can anticipate the breakdown of building components and prepare the required resources. 3 D visualization appears in MAFMS dashboard. To do so, engineering drawings of the selected hospital are used to build a 3D floor plan in Anylogic.

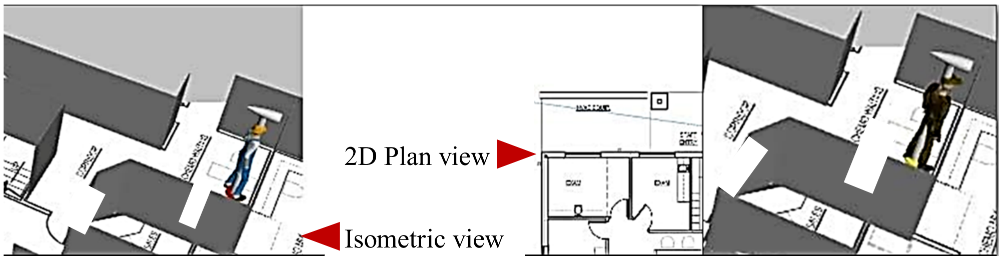
The case study focuses on the maintenance of the service elevators in the selected hospital. The hospital elevators are considered as BCAs, with their maintenance data stored in the relevant database (e.g. the preventive maintenance schedule). Elevators have different maintenance behaviors, including operating, failed, repair, replacement, and scheduled maintenance at set time intervals. In addition, elevators have operating behaviors, including idle and busy, which are controlled by a Controller System (CS). The CS arranges the elevator car function as a consequence of the internal and external requests. In this study, the maintenance workflow of service elevators is modeled. The Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR) are two parameters, which are used to set up the maintenance behavior of the elevators. The probability of the failure of the elevators and their routine maintenance schedule are incorporated into the MARAS. Therefore, facility managers can track the operation of elevators and predict the time of their failure, as well as track the preventive maintenance schedule of each elevator for allocation of resources. Figure 5-7, the state chart illustrates the operation and maintenance function of the elevators (Phase 6). Consequently, human resource agents' behaviors are also modeled (Phase 6) in this simulation.

Simulating the movement of resources in a hospital provides a dynamic visualization of that environment. Therefore, Pedestrian Library, which is embedded in Anylogic, is employed to simulate the movement of resources in the 3D floor plan of the hospital building. The use of the

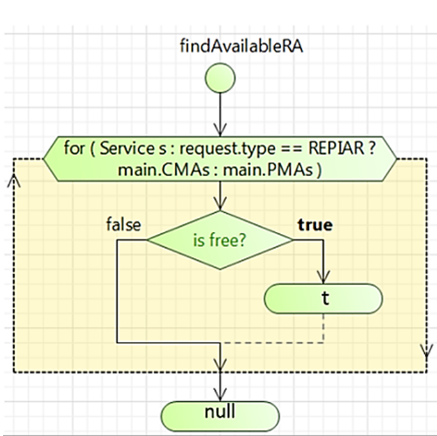
Pedestrian library is significant for its basic rules. These rules help us to control the resource movement attributes such as movement rates, speed, orientation, and distance adjustment. In this sense, the RAs can move between physical obstacles to reach the BCAs and back to the office in a continuous space. In the developed model, the Environment Objects and Space Markup Shapes are also used to build a convincing animation. The developed dynamic 3D visualization of MARAS provides a virtual laboratory environment to test different scenarios of resource allocation.

Architectural floor plans are used to determine the location of elevators in the hospital building. Then each elevator is marked by an indicator. These indicators are representative of elevators in the building, which are placed in the architectural plan of the building. While the elevator is performing optimally (in the Operating state), the indicator light remains green. When the elevator is failed (Failure interaction is activated based on its failure rate) the new order is generated and added to the coordination queue. Simultaneously, the related indicator becomes red on the screen as shown in Figure 5-14 (a). FMA sends a message to the available TCA for evaluating the order. TCA checks the coordination queue and moves to the location of the failed BCA. After inspection, TCA sends the verification code to FMA. After the order is added to the high, low priority queue, scheduled queue, FMA checks the availability of CMA. The collection iterator loop, within an action chart, shows this activity (Figure 5-14 (b)). FMA asks CMA to initiate repairs and adds the order in the execution queue. After execution (repair or replacement) the order is placed in the supervision queue. TCA moves to the indicator (BCA) to confirm the elevator operation. Similarly, if the elevator requires inspection based on the preventive maintenance schedule, the indicator turns yellow, and the order is placed in the scheduled queue. In this case, the FMA sends a request for inspection to the PMA.

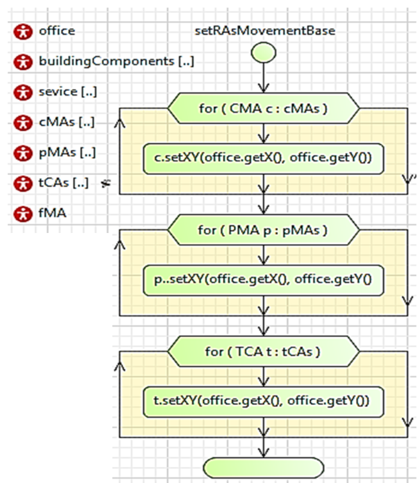
Resource movement time is considered in simulation model and SBO. A set of functions is defined for moving RAs in the building, including locating building components and FM office, obtaining the current location of RAs, defining the direction of movement of RAs to reach the target location in the 3D plan, calculating the distance between the specific locations in building plan, determining the walking speed of the RAs and finally adjusting the automatic rotation of the RAs while moving across the 3D plan. The average initial speed of resources movement in the building is set 10 miles per hour. The agents' movement starts from the office to the BCAs for repair, maintenance, and inspection. Therefore, the action chart is used to specify the coordinates of the starting and ending points of the RAs movement in the building as shown in Figure 5-14(c).



a) Screenshot of CMA, PMA on 3D visualization of MARAS



b) FMA search for available CMA



c) Set up CMA, PMA and TCA movement

Figure 5-14. 3D visualization of MARAS.

5.4 Results and Discussion

In this chapter, two simulation models and one SBO model were developed and implemented. In the following, the results of the models are presented, analyzed and validated.

5.4.1 Simulation Results

The performance of building components and resource utilization of the case study were simulated and studied using workflow process model and MARAS. A clear understanding of the current situation is defined using the developed simulation models. Annual average statistics of elevators performance and annual number of maintenance functions for an elevator are shown in Figure 5-15 and Figure 5-16, respectively. Figure 5-15 shows that about 7 out of 10 elevators were available for use during the year. Figure 5-16 represents the cumulative total percentages of an elevator maintenance functions over a year. By analyzing this Figure, it can be concluded that in the current situation of the case study, some elevators are broken and waiting for the service crew. The accuracy of the simulation results was confirmed by the Facility Manager of Madar hospital. The interpretation of this result has been justified by the results of the simulation in Figure 5-20 (a). As shown in Figure 5-20 (a), the annual uptime of the elevators was approximately 70% implementing MARAS.

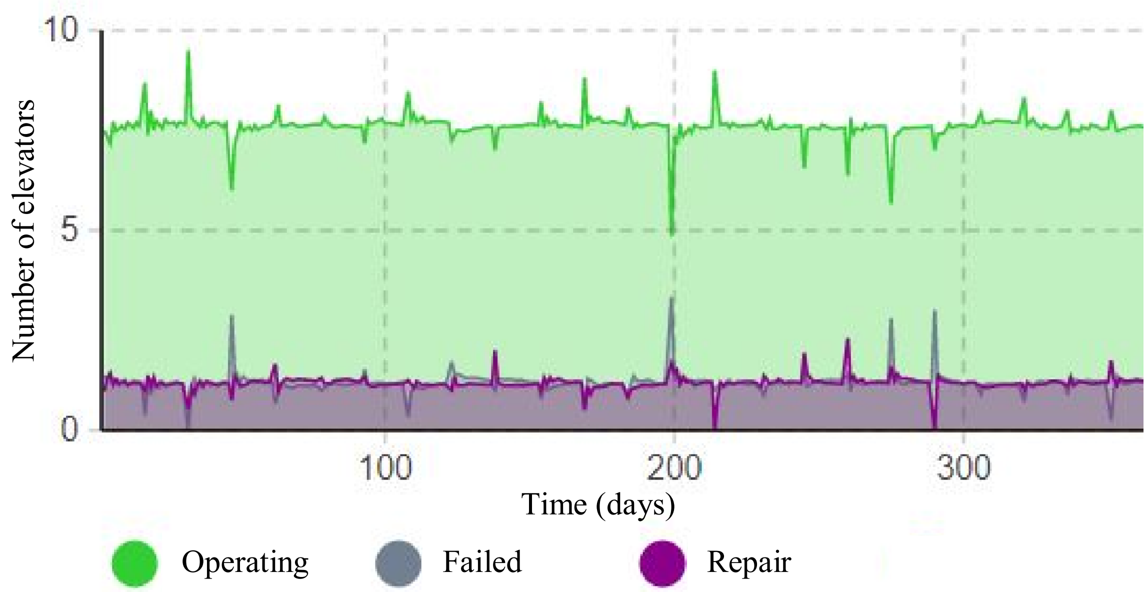


Figure 5-15. Time stack chart for elevators maintenance function in a year.

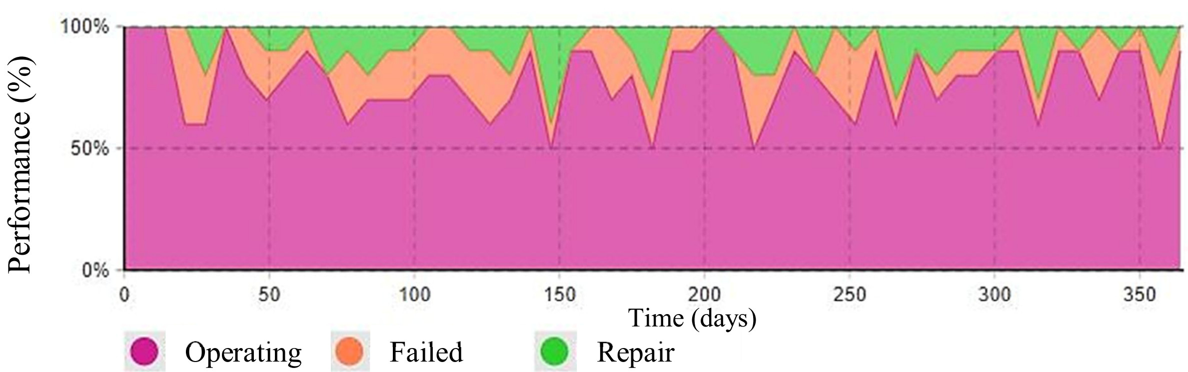


Figure 5-16. Time stack chart for an elevator performance in a year.

In order to achieve one of the objectives of this study, simulation results were used to estimate resources utilization over a year. Figure 5-17 shows the total time spent on maintenance activities by TCA in one year before and after the implementation of MARAS. Figure 5-17 (a) shows that TCA is Idle for 27%, while he spends only 29% of his work time inspecting and 26% preparing reports. This has a negative effect on other activities in the maintenance workflow process and causes the building components to remain in failure condition for a longer period of time. Therefore, it can be concluded that the current method of resource allocation in the case study is not time efficient. Various resource compositions are tested by applying what-if scenario analysis to generate a near-optimal schedule. By applying the what-if scenario analysis the positive and negative effects of changes are evaluated on the project objectives and fulfil the FM requirements. Figure 5-17 (b) shows that after implementation of the developed simulation model, TCA has less idle time, more movement, and more inspection time.

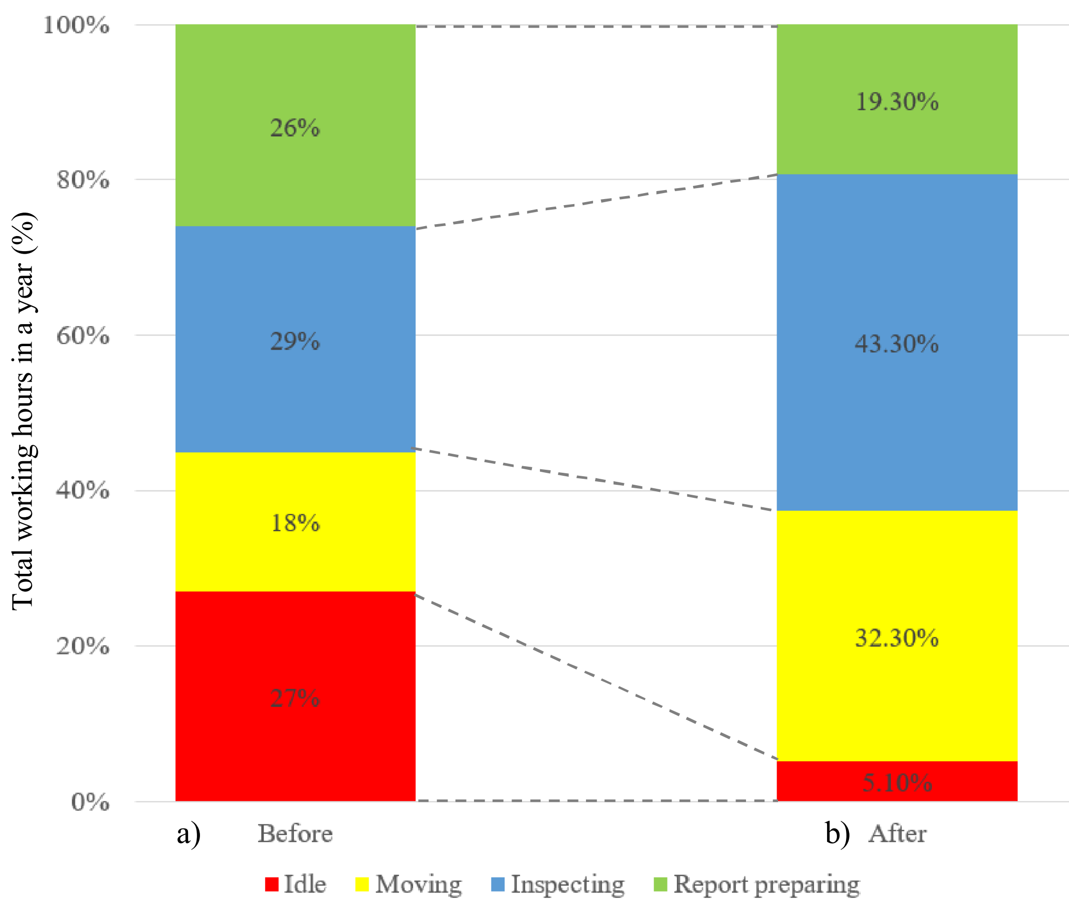


Figure 5-17. TCA working before (a) and after (b) implementation of the MARAS.

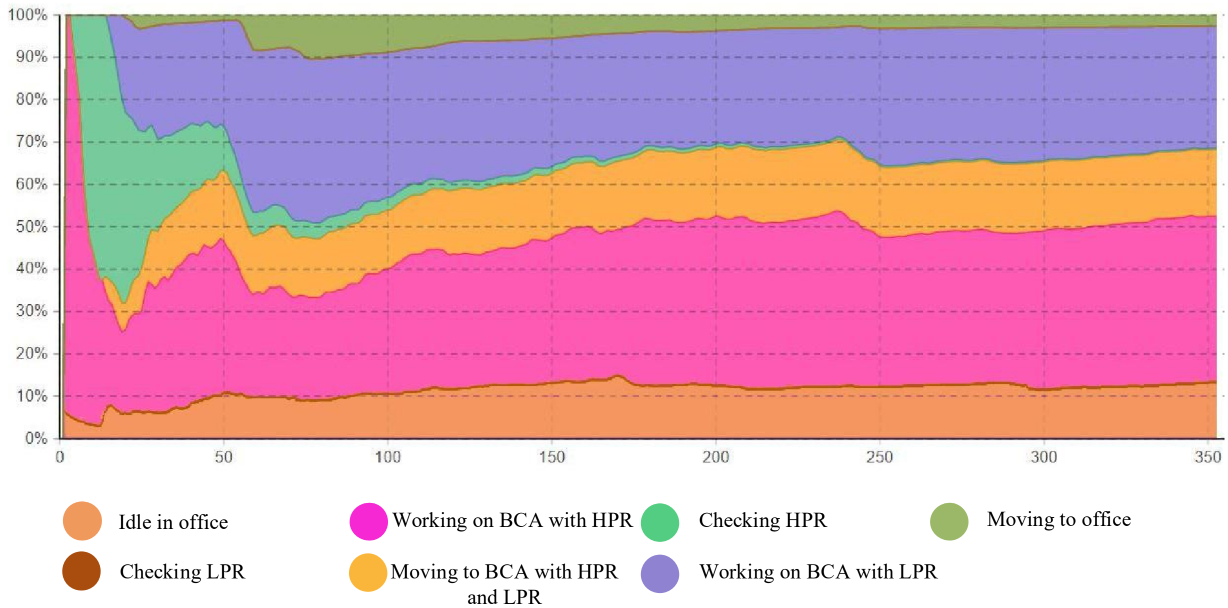


Figure 5-18. Time stack chart for CMA utilization.

The CMA must perform a variety of activities, including checking High Priority Requests (HPR) and Low Priority Requests (LPR), moving to the location of building components and FM office, repairing or replacing, and adding the executed order to the supervision queue. Figure 5-18 indicates the average working time of the CMA in a year. Therefore, according to simulation results, CMA spends 11% of the time on: 'Idle in office", 5.7% on "Checking HPR and LPR", 18% on "Moving to BCAs and FM office", and finally 65.3% on "Working on BCA with HPR and LPR" after the implementation of MARAS. Table 5-15 demonstrates the CMA utilization in a year before and after the implementation of MARAS. According to this Table, after the implementation of the proposed system, the CMA has less idle time and checking time, while he has more movement and working time.

Table 5-15. Yearly working time of the CMA before and after implementation of the MARAS.

CMA activities		**Idle in office**	**Checking**		**Moving to BCA with HPR and LPR**	**Moving to office**	**Working on BCA with**	
			HPR	**LPR**			HPR	LPR
Working time	**Before**	28 %	8 %	4 %	10 %	7 %	33 %	10 %
	After	11%	4.3%	1.4%	13.9%	4.1%	36.7%	28.6%

Figure 5-19 illustrates the time stack chart for PMA utilization. According to simulation results, PMA spends in average 25% of the time on: 'Idle in office", 30% on "Moving to BCA", 35% on "Moving to office", 7% on "Working on ACheck", 2% on "Working on BCheck", and finally 1%

on “Working on CCheck”. From this Figure, it can be clarified that PMA responsibility can be considered as a shared duty with other resource agents or it can be outsourced.

Since one of the objectives of this study is to measure the performance of building components in hospitals, the performance of elevators was studied under the aforementioned failure rate and maintenance conditions. A comparison of the simulation results shown in Figure 5-20 (a) and (b) shows that the annual downtime of elevators decreases from 2,628 to 263.16 hours in a year (8760 hours). In other words, implementing MARAS reduces the waiting time for service from 109 days to 11 days approximately and increases elevators performance by 97%.

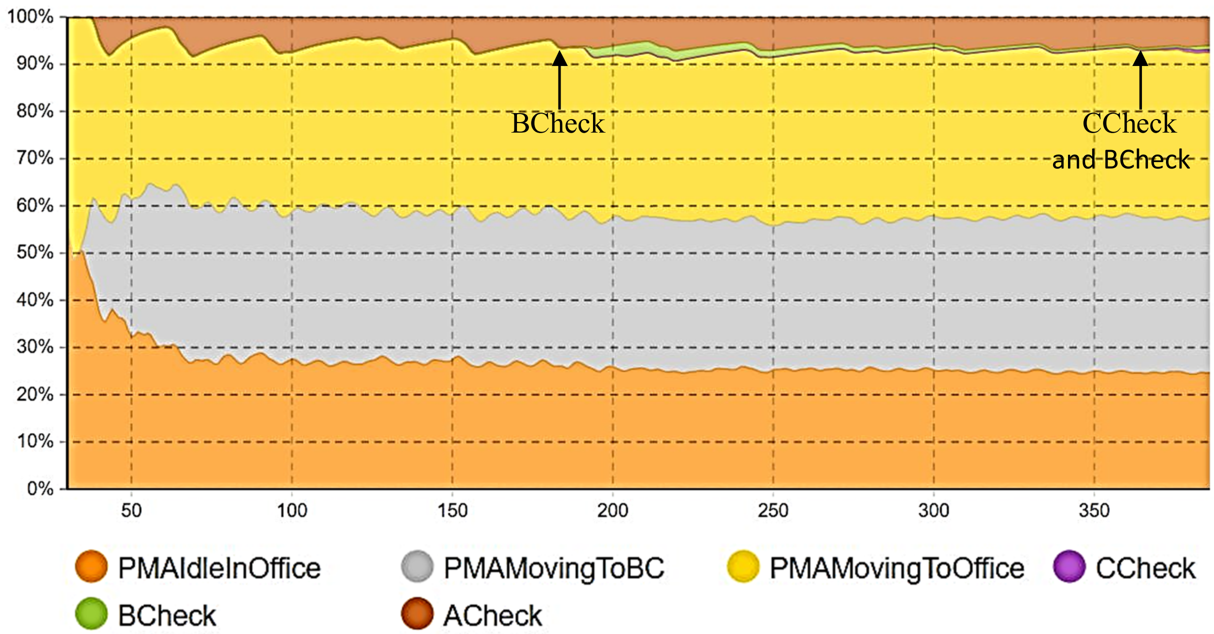
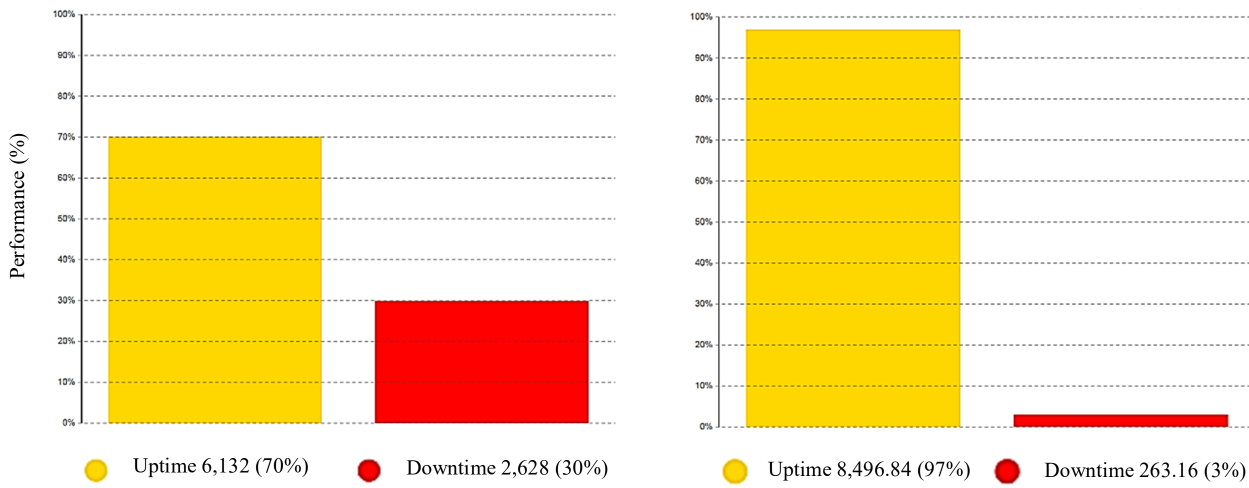


Figure 5-19. Time stack chart for PMA utilization.

In summary, MARAS simulates resource allocation as well as the dynamic environment of building components repair and maintenance, estimates the resource utilization for a specified period of time, and measures the building components performance in a specified period of time. Using the developed simulation model, facility managers can measure the percentage of time spent by each human resource for maintenance activities over a specified period of time. By studying these percentages, facility managers can evaluate the efficiency of the current method of allocating resources in buildings. Inefficient resource allocation causes building components to remain in a state of failure for a longer period of time while waiting to be repaired.



a) b)

Figure 5-20. Yearly performance (Uptime, Downtime) of the elevators before (a) and after (b) implementation of the MARAS.

5.4.2 Sensitivity Analysis of Simulation Model

The simulation outputs were examined under a variety of input parameter changes to ensure that the model is constructed properly. The simulation model was validated using the sensitivity analysis method. This experiment showed how the simulation output (e.g., Average availability of the elevators in a year) depends on changing one of the model input parameters, which was MTBF (Figure 5-21). Figure 5-22 shows the results of the sensitivity analysis experiment. Since the rate of change of the model output is very small, it can be concluded that the effect of potential error in the simulation model is minimal. To enhance the validity of the model, in addition to sensitivity analysis, simulation results have been shared with experts, stakeholders, and facility managers to examine whether these results can meet their expectations. So, statistical results are discussed with the FM team at the Madar hospital.

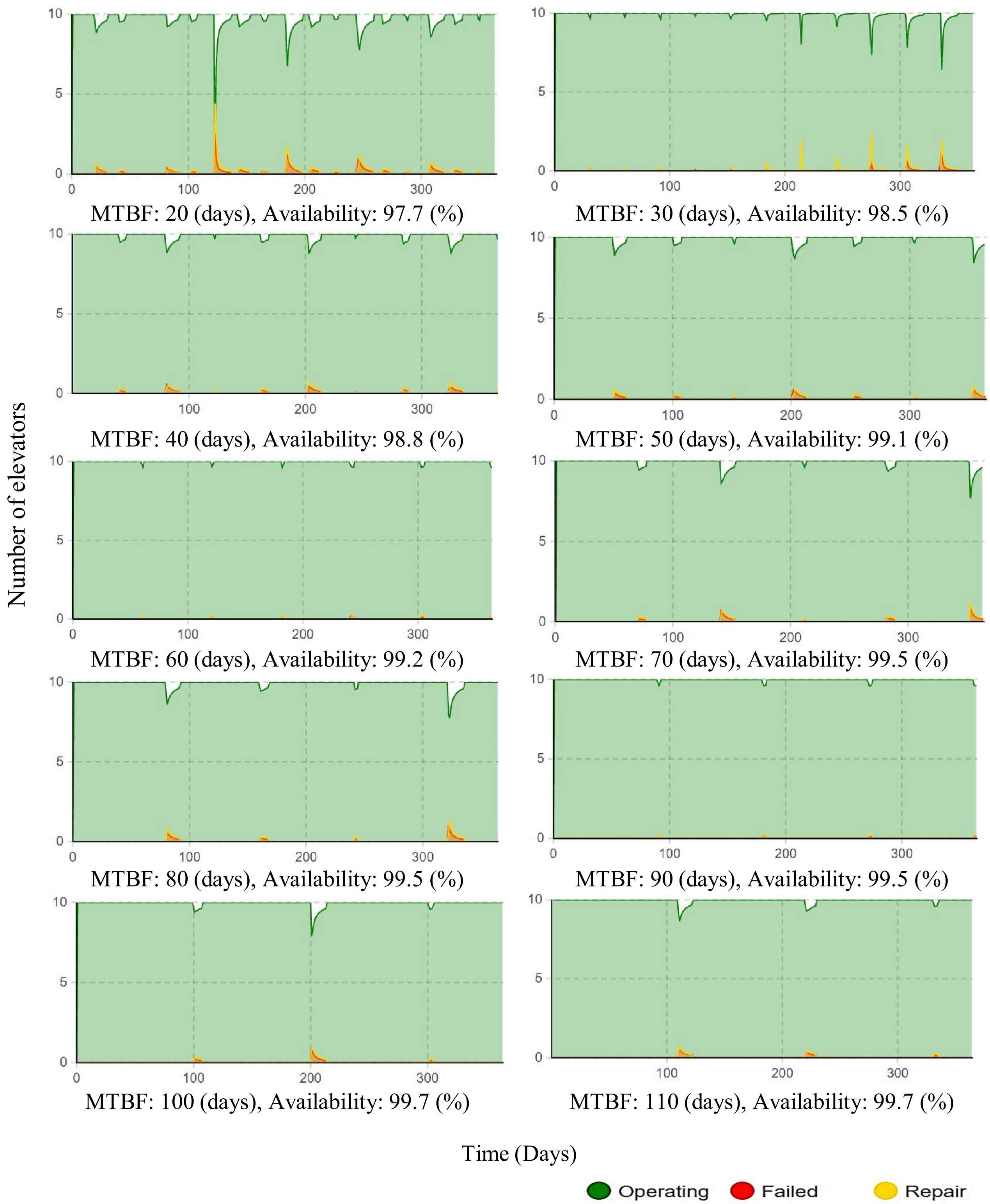


Figure 5-21. Different scenarios of MTBF (input) vs. availability (output).

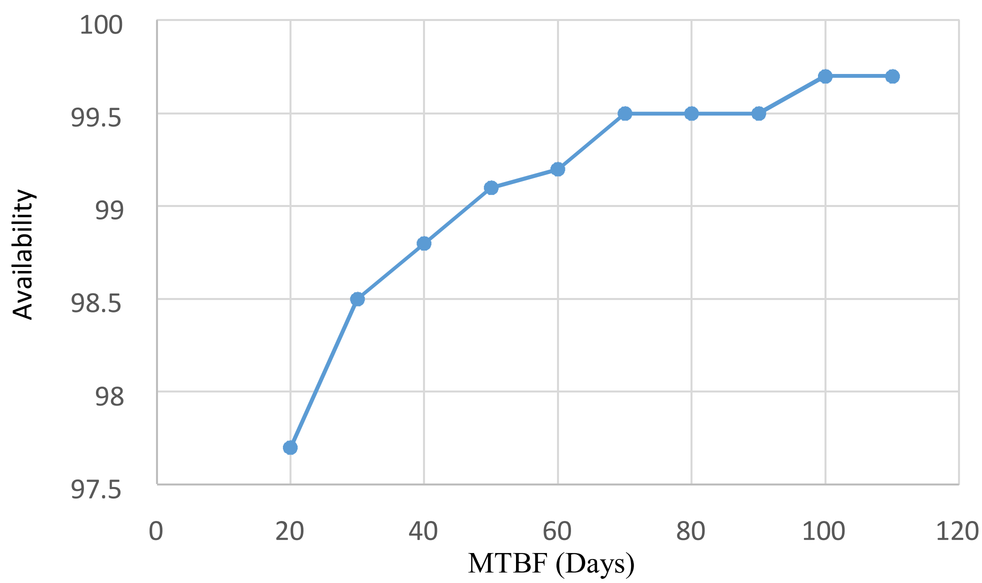


Figure 5-22. Sensitivity analysis.

5.4.3 SBO Results

In this study, the maximum number of iterations of optimization is set to 350, while for each iteration, 10 replications are performed. The optimization procedure was repeated until the condition of convergence was fulfilled or the termination conditions achieved (i.e., the number of iterations or simulation time).

The results of the optimization, which are the mean annual down-time of elevators are shown in Figure 5-23. In this Figure, the vertical axis is the mean annual down-time value (objective function), while the horizontal axis is the number of iterations. The results of the optimizations are shown as a convergence graph. In Figure 5-23 the blue line indicates the mean annual down-time of the best feasible objective function.

The grey dots indicate the mean annual down-time of the current objective function for a particular simulation run. Each dot in the chart represents an iteration in the solution space. The solution space is [1..5]*[1..2]*[1..5]*8,760= 438,000 points. Important parameters for the evolutionary algorithm used in this study include the number of generations run (350), the population size (100), the probability of mutation (0.3), and the probability of crossover (0.80) (More information has been provided in Appendix H). The termination criterion is set to 350. The optimizer found the best parameter values for the resource combination as shown in Table 5-16.

Table 5-16. Optimization results.

variables	Current situation	Best result
n_{CMA}	3	2
n_{PMA}	2	1
n_{TCA}	3	2

As shown in Table 5-17, the best solution found after 43 iterations. A combination of 2, 1, and 2 resources for CMA, PMA, and TCA should be allocated to elevators repair and maintenance to have the minimum feasible annual down-time. Under these conditions, the estimated mean annual down-time of elevators is 280.38 hours in a year. So, the mean annual up-time of elevators is 8479.62 hours in a year. It can be concluded that by implementing the proposed model, elevators are available on average 96.79 % in a year.

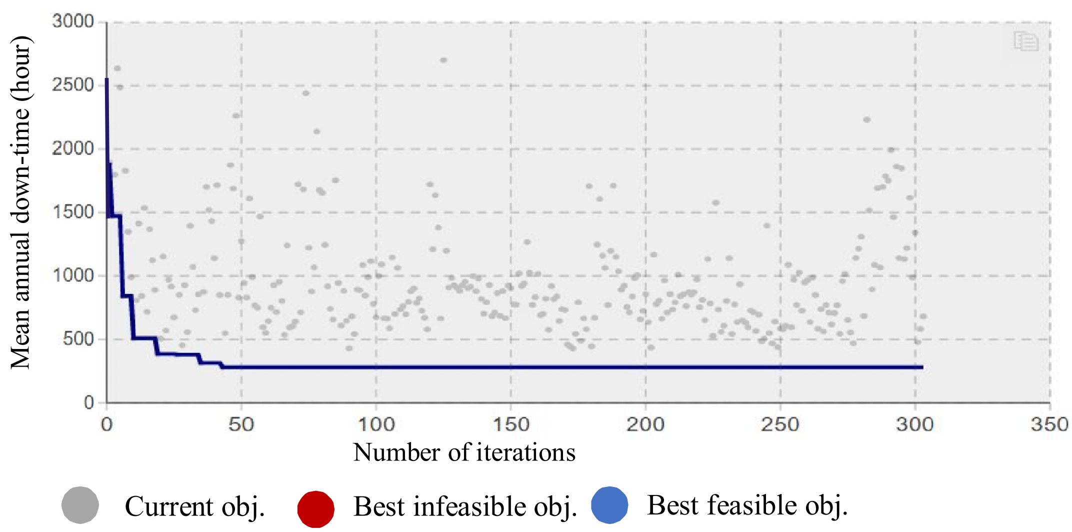


Figure 5-23. Optimization result of mean annual down-time (availability ≥ 80%).

Table 5-17. Optimization results for availability ≥ 80%.

Name	Current situation	Best results
Iterations completed	303	43
Replications	10	10
Objective	681.35 (hours)	280.38 (hours)

5.4.4 Sensitivity Analysis of SBO Model Results

Sensitivity analysis was performed to analyze the effect of changing the values set for constraints on the optimization results. To test the validity of the optimization model, the minimum threshold of elevators availability, as one of the optimization constraints, is changed and is set at 90%. Therefore, it is assumed that the mean availability of elevators must not be less than 90% in a year. The sensitivity only aims at values between 90% down to 80% but is not going further down as to meet the minimum availability (uptime) requirements. The constraint value is changed as shown in equation (10), while equations (7), (8), (9), and the solution space remain constant.

$$90\% \leq \frac{\sum_{i=1}^{365}(\frac{n_i}{n})}{365} \tag{10}$$

where,

i is days, n_i number of elevators in operation on the ith day, n is total number of elevators.

Then the optimization is run according to equation (10) and the results are displayed in Figure 5-24. As shown in Table 5-18, the best solution found after 33 iterations. Under this condition, the estimated mean annual down-time of elevators is 184 hours in a year. So, the mean annual up-time of elevators is 8576 hours in a year. So, the elevators are available on average 97.89 % in a year.

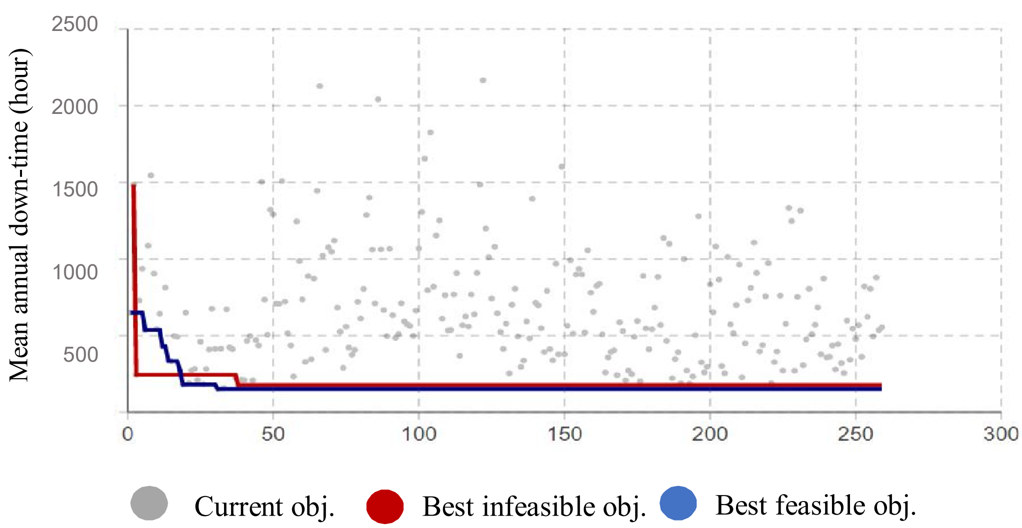


Figure 5-24. Optimization result of mean annual down-time (availability ≥ 90%).

Table 5-18. Optimization results for availability ≥ 90%.

Name	Current situation	Best results
Iterations completed	259	33
Replications	10	10
Objective	1108.32 (hours)	184 (hours)

The combination of 2, 1, and 2 resources for CMA, PMA, and TCA is the best feasible solution, which is not changed by revising the constraint values from 80% to 90% (equation (6) and equation (10)). The difference between the availability of the elevators in two different optimization runs is 1.1% (96.96% and 97.89%), which is not significant. Hence, the percentage of changes in optimization results in this case study, indicates that optimization is not sensitive to increasing the minimum threshold of elevators availability from 80% to 90%.

Workflow process model and MARAS are two components of the developed simulation model, simulating the maintenance requests tracking process as well as resource allocation. A facility manager could track the maintenance order status through workflow and measure the extent of waiting time for these orders in different queues. Moreover, developing MARAS enables the facility manager to investigate and formulate the interaction between resources and orders through the means of simulation. Such a simulation, supported by a dynamic 3D visualization model of the hospital building, provides a means of visualization for facility managers, which will assist in informed maintenance resource allocation decisions.

5.5 Summary and Conclusions

Facility managers are faced daily with an extensive amount of maintenance requests and related orders in an environment characterized by fragmented information associated with building physical components and diverse maintenance resources. The handling of orders and affiliated information is further complicated because of the dynamic nature of the maintenance environment. Unexpected failures causing repeated changes to preventing maintenance schedules and creating challenges in the allocation of resources for needed maintenance operations. The literature reveals that the dependent information about the maintenance activities is highly fragmented, complicating, and delaying the decision-making process about maintenance resources and their allocation. To address the above issues, this study paid particular attention to the role of coordinating and integrating the different levels of maintenance management. Moreover, a new method was developed to assist in informed decision-making. The MAS model was employed as a distributed system to compensate for the shortcomings of a centralized systems. Using the developed method, maintenance decision-making in hospitals would be more time-efficient, relying more on the simulation of future scenarios and visualization of their consequences instead of relying on the current maintenance management system.

The main objective of this thesis is to minimize the down-time of elevators as components of the case study. To this purpose, DES model was developed to simulate and facilitate workflow processes for FM. So, the facility manager can monitor the number of orders in different queues at real-time. In addition by developing an agent-based model, the resource utilization can be measured and modified. Finally, SBO model, is incooperated in the simulation model, providing the optimal number of resources allocated to elevators maintenance activities to minimize elevators down- time. Consequently, two simulation models were developed to simulate and analyze resource allocation in maintenance of hospital buildings. The workflow process model was developed to monitor the maintenance management process through the means of DES. The MARAS step investigates the coordination and communication among facility managers, resources, and supervisors, as well as building components, which were defined as agents. The developed simulation model helps facility managers predict any changes in the maintenance plan and schedule, by testing different future scenarios of resources as well as failure incidents. An interactive simulation and visualization model has been developed for facility managers that considers workflow and resource allocation parameters. This model tracks resource allocation decisions and their consequences over time.

The maintenance information of the Madar hospital and its architectural plans are used to simulate and analyze the current maintenance status of the elevators. The simulation results show that the annual uptime of the elevators was approximately 70% in the case study. MARAS can be used by FM for the evaluation of several what-if scenarios before reaching a conclusion and making a decision. After the implementation of MARAS, the simulation results show that the performance of elevators increases to 97% due to the reduction of maintenance delays. This happened while the failure rate of the elevators did not change. A SBO model has been developed that optimizes the mean annual down-time of building services components (e.g., hospital elevators), while meeting the minimum acceptable availability of elevators at least 80%. The output of the optimization model showed that the mean annual down-time of elevators can be substantially reduced if the optimal number of resources is allocated to their maintenance. The results of the sensitivity analysis in this particular case study showed that increasing the minimum acceptable availability of the elevators from 80% to 90% does not significantly affect the optimization results. Therefore, it was found that the SBO results were acceptable.

CHAPTER 6. SUMMARY AND CONCLUSIONS

6.1 Summary

This research provided a general background and a review of the literature related to facility management of hospitals and identified current research gaps. This study focuses on applying the agent-based approach in the context of FM in hospitals for maintenance resource allocation. The proposed method consists of a set of three developed models described in Chapter 3. This study introduces a newly developed automated method and describes its implementation in a case study to validate the applicability of the developed method and its models. Chapter 4 focused on the development of MAFMS as the first model, while Chapter 5 discussed the development of two other models, the MARAS and SBO models. The sensitivity analysis method was used to validate the developed simulation and optimization models. In addition, the SBO model was developed in Chapter 5. This model can be used to identify the near-optimal number of resources while minimizing down-time of building components. Therefore, facility managers can re-engineer the resource allocation plan using SBO.

In summary, the main achievement of this study is the development of an integrated order tracking-resource allocation method, which combines the fragmented information within the different levels of maintenance management. This integration allows a structured exchange of information. This method enables facility managers to make decisions that are both timely and efficient. As a result, the delay in responding to maintenance requests is reduced, which can indirectly result in enhancing the patients' satisfaction.

6.2 Contributions and Conclusions

The following highlights the main contribution of this research.

1) Addressing issues that affect "deferred maintenance" in hospitals, including inefficient workflow management and resource allocation through the development of an innovative system using MAS to manage workflow and allocate resources for maintenance activities in hospital buildings, overcoming the inefficiencies associated with centralized systems. Centralized systems do not account for decision-making processes in a complex environment such as a hospital. Regarding this contribution, the uniqueness of this development is that MAS is able to process

data and respond to user inputs with a delay of only a few minutes. In fact, the developed system is a near real-time system that can reduce the response time to maintenance orders. Therefore, using this system can reduce maintenance delays in hospitals.

2) Development of MAFMS to support facility managers' decision-making process by capturing maintenance order information, storing it in the system, planning the maintenance process, allocating resources to the maintenance tasks, coordinating among resources, supervising the performance of the resources, documenting the operation, and updating the real-time maintenance schedule for in-house resourcing maintenance operations. Through this system, maintenance information related to resource allocation and scheduling is effectively linked to provide timely feedback for decision-makers. To this end, the workflow management is integrated with resource allocation planning to facilitate the resource adjustments needed in response to dynamic changes and requirements over the entire maintenance process. This integration not only facilitates access to the data needed for maintenance activities but also enables resources to communicate in the fastest and easiest way.

3) Development of simulation models to demonstrate the benefits of the MAFMS to reduce the response time to maintenance requests. To this end, a multi-agent simulation was developed to simulate the behavior and the interaction among facility managers, human resources, and supervisors to effectively maintain building components and ensure their targeted performance. Hence, MARAS simulation provides an opportunity for facility managers to evaluate various resource allocation scenarios, and reconfigure their allocation plan, if needed.

4) The simulation model acts as a virtual laboratory for facility managers and enables them to evaluate different resource allocation plans. MARAS can be used by FM for the evaluation of several what-if scenarios before reaching a conclusion and making a decision. The resource allocation plan can be modified, where the composition and number of resources become near-optimal. In this regard, a SBO model has been developed to select the best combination of resources while respecting the availability of building components.

MAS, as a distributed system, enables decision-makers to observe the impact of changes on systems and allow them to make better decisions and predictions. The outcomes of the proposed method will be useful for maintenance managers, practitioners, stakeholders, and policymakers concerned with FM of hospital buildings and healthcare facilities.

6.3 Limitations and Future Work

Although this research has successfully achieved its goals, some limitations and challenges remain and need to be addressed in the future. The limitations and future works are as follows:

- Translating the resource allocation problem into an agent-based schema and modeling this problem in the appropriate software is time-consuming and costly. Therefore, creating an efficient platform for MAS development is essential. It is also recommended, that a standard method should be developed for modeling, simulating, and validating highly complex MASs.
- Full development and implementation of the proposed MAFMS requires industry partners and stakeholders to provide relevant information to support the system.
- Access to accurate data is challenging as the majority of the required data for maintenance management in most hospitals is still paper-based and not well documented. Using sensors in hospitals would be a way to gather more information about maintenance methods and the condition of building components.
- From the perspective of the tools used in this research, Anylogic allows users to integrate all types of simulation methods (i.e., SD, DES as well as ABM techniques) into one file. During modeling, Anylogic allows users to add their program code lines to manage any event. Therefore, in this study, a multi-method simulation approach has been developed to integrate segmented information at different levels of maintenance management, i.e., workflow process and resource allocation. Although Anylogic is a powerful tool to model a dynamic environment, it is an extremely complicated modeling tool. Therefore, future efforts could focus on developing other simulation software to facilitate the modeling of complex problems.

Future work will focus on the following topics:

- MAFMS has the potential to connect to third-party systems, such as Closed-Circuit Television (CCTV), Radio Frequency Identification (RFID), and alarm systems. Joining these systems to MAFMS would facilitate and expedite the maintenance workflow, for example, RFID may use to send a failure notification of a building component to the WRCA.
- In this study, resource allocation is simulated using in-house human resources information. Therefore, a parallel or complementary multi-agent simulation model can be developed to work

with outsourcing information. The development of an outsourcing model, and the evaluation of its resource performance and reporting model, is also an avenue for future research.

- MARAS can be extended to simulate the performance and maintenance functions of other building components.
- The components of cost were not quantified in the developed optimization model. Maintenance budget can be considered as an additional constraint associated with resource allocation optimization. Therefore, maintenance cost optimization can be considered in future studies.

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APPENDICES

Appendix A: Interview with Facility Manager of Madar Hospital

Q1- What are the main components of a building that need a maintenance plan?

A1- The following table summarizes the maintenance plans of the main components, equipment and systems in the building:

Main Components	Maintenance plan
Elevators	Inspection (every month, every six months and every year) with in-house personnel
Electrical lightings	Inspection of all emergency lights and change of batteries with in-house (Every week)
Fire protection system	Maintenance with contractor (outsourced)
Control system	Building Automation System (BAS)- Diagnose problems
HVAC	Inspection and repair with both in-house and contractor
Interior components and furniture	Inspection with in-house
Replacement of defected components	Replacement with in-house personnel, corrective maintenance resources (CMR)
Emergency facility management	Emergency plans for fire, earthquake, power failure etc.
Facades of the building	Inspection with contractor (outsourced)
IT systems	IT department is in charge
Security of the building	Security department is in charge

Q2- What is the type of maintenance management method in your organization?

A2- CMMS is used as a tool for maintenance management.

Q3- What are the types of maintenance strategies in your organization?

A3- The hospital works with two maintenance strategies including corrective maintenance (CM) and preventive maintenance (PM).

Q4- Any preventive methods for maintenance are used?

A4- We have a preventive maintenance plan for vital building components such as elevators.

Q5- How often should elevators be inspected according to preventive maintenance?

A5- Elevator components must be inspected monthly for general inspection, every six months for mechanical and electrical issues, and annually for comprehensive inspection.

Q6- How many employees work in the FM team (in-house)?

A6- There is 1 facility manager, 3 mechanical engineers, 3 electricians and 5 technicians in FM team of Madar hospital.

Q7- How many work orders are received per day –on average- due to unexpected failure of the building systems or components? (Number of orders in registration queue)

A7- On average, we receive 10 to 15 work orders per day, which are related to the breakdowns of vital building components.

Q8- Is there any outsourcing in FM of Madar hospital?

A8- Yes. 48 contracts have been signed for vital and high value medical equipment in the hospital.

Q9- Are you aware of using the simulation model to provide better performance?

A9- Yes, the facility manager is aware of the benefits of simulation such as testing different conditions without affecting the actual situation, but we do not have such a model.

Q10- To what extent do you think simulation models are used in facility management? If it is little, what do you think are the main challenges (technological and organizational)?

A10– Very limited. There are several challenges, such as the complexity of the maintenance environment. There is insufficient awareness about the benefits of using simulation models. In addition, there is insufficient training to develop and use simulation models for FM.

Appendix B: Survey Questionnaire- Part 1

EVALUATION OF THE CURRENT RESOURCE ALLOCATION PLAN

Q1) Is your organization a hospital/ medical facility or not?

Yes	☐
No	☐

1) Building Information

Q2) What is the total square footage of your building (Net area (m^2))?

Less than 2,000	☐
Between 2,000-5,000	☐
Between 5,000-10,000	☐
More than 10,000	☐

Q3) What is the age of your building?

Less than 10 years	☐
Between 10-30 years	☐
Between 30-50 years	☐
More than 50 years	☐

Q4) What is the number of visitors of your building per day (including employees)?

Small hospital (less than 50 persons)	☐
Medium hospital (between 50-100 persons)	☐
Large hospital (between100-200 persons)	☐
Large hospital (more than 200 persons)	☐

Q5) How many elevators are in the building?

Less than 3	☐
Between 3-6	☐
Between 6-10	☐
More than 10	☐

2) Technology Assessment (Computer Maintenance Management System (CMMS))

Q6) What is the type of maintenance management method in your organization?

Paper-based system (non-automated service management process)	☐
Automated Service Management (SM) process	☐

3) Work Orders (e.g., HVAC, Lighting, Elevator)

Q7) How many work orders are received per day –on average- due to unexpected failure of the building systems or components? (Number of orders in registration queue)

Less than 5	☐	5-10	☐	10-15	☐	More than15	☐
Other (please specify ……………………………………………………………….…………..)							

Q8) What is the percentage of rejected work orders (deemed not valid by the inspector)?

Less than 5%	☐	Between 5-10%	☐	Between 10-20%	☐	More than 30%
Other (please specify ……………………………………………………………….…………..)						

Q9) How often, approximately, facility management team receive orders (repair requests) by appropriate authorized personnel per day? (Inter arrival time).

Every hour	☐
Every 2 hours	☐
Every 4 hours	☐
Every day	☐
Other (please specify ……………………………………………………………….……….)	

Q10) What is the <u>average waiting time (in minutes)</u> for each order in the <u>registration queue</u> to receive response from the <u>service crew</u>?

Less than 30	☐	Between 30-60	☐	Between 60-120	☐	More than 120	☐

Q11) What is the <u>average waiting time (minutes)</u> for each order in the <u>supervision queue</u> to receive responses from the <u>supervisor</u>?

Less than 30	☐	Between 30-60	☐	Between 60-120	☐	More than 120	☐

Q12) What <u>percentage</u> of work orders sent back to <u>rework queue</u>?

Less than 5%	☐	Between 5-10%	☐	Between 10-20%	☐	More than 30%	☐
Other (please specify……………………………………………………….….….…………)							

4) Prioritization of Orders Assessment

Q13) How does the facility manager of your organization/hospital arrange orders at execution queue? (What is the queuing discipline?)

FIFO (first-in, first-out)	☐
LIFO (last-in, first-out)	☐
Priority-based	☐
Other (please specify ………………………………………………………….…….)	

5) Human Resource Allocation Assessment

Q14) Indicate the total time (in hours) a Corrective Maintenance Resource (CMR)-service crew spends on the following activities in a 40 hours-week?

	Less than 5	Between 5-10	Between 10-15	Between 15-20	More than 20
Repair	☐	☐	☐	☐	☐
Replacement	☐	☐	☐	☐	☐
Report preparation	☐	☐	☐	☐	☐
Movement	☐	☐	☐	☐	☐
Waiting in office	☐	☐	☐	☐	☐
Exchanging the Information	☐	☐	☐	☐	☐

Q15) What is the total time (in hours) a Preventive Maintenance Resource (PMR)-service crew spends on the following activities in a 40 hours-week?

	Less than 5	Between 5-10	Between 10-15	Between 15-20	More than 20
Inspection	☐	☐	☐	☐	☐
Routine maintenance	☐	☐	☐	☐	☐
Report preparation	☐	☐	☐	☐	☐
Movement	☐	☐	☐	☐	☐
Waiting in office	☐	☐	☐	☐	☐
Exchanging the Information	☐	☐	☐	☐	☐

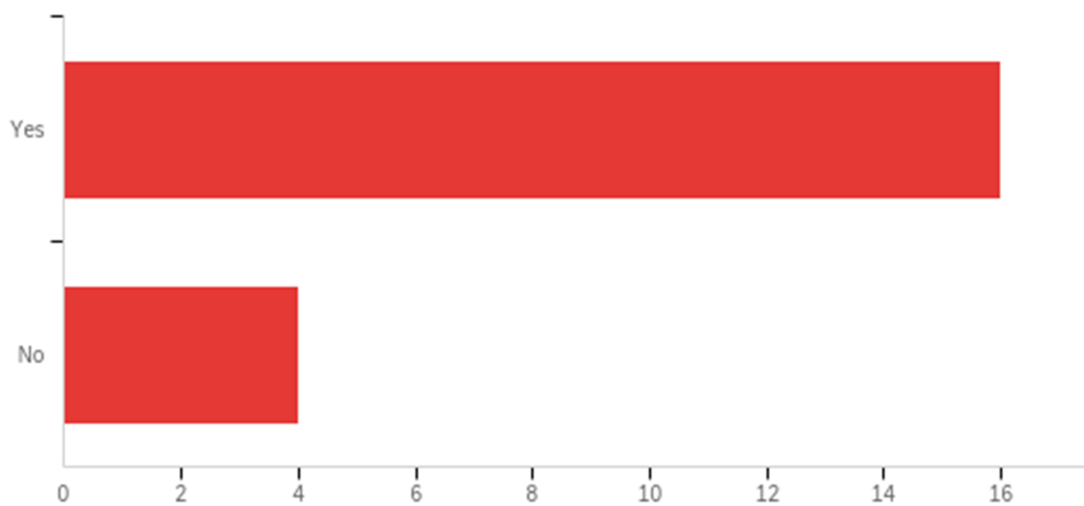
The survey (Part 1) was hosted on:

https://qfreeaccountssjc1.az1.qualtrics.com/jfe/form/SV_3QrNSk2lqcodzYV

Appendix C: Survey Results Analysis and Discussion- Part 1

Q1 - Is your organization a hospital/ medical facility or not?

This questionnaire was distributed to 30 maintenance experts and facility managers via email. 20 people participated in the survey. Survey findings are used to understand the current state of facility management in hospitals and simulate workflow management and resource allocation in the software environment. In addition, this data is used as input data to implement and run the simulation models. As shown in following Figure, 80% of the participants are facility managers and engineers working in maintenance activities in hospital or health centers.

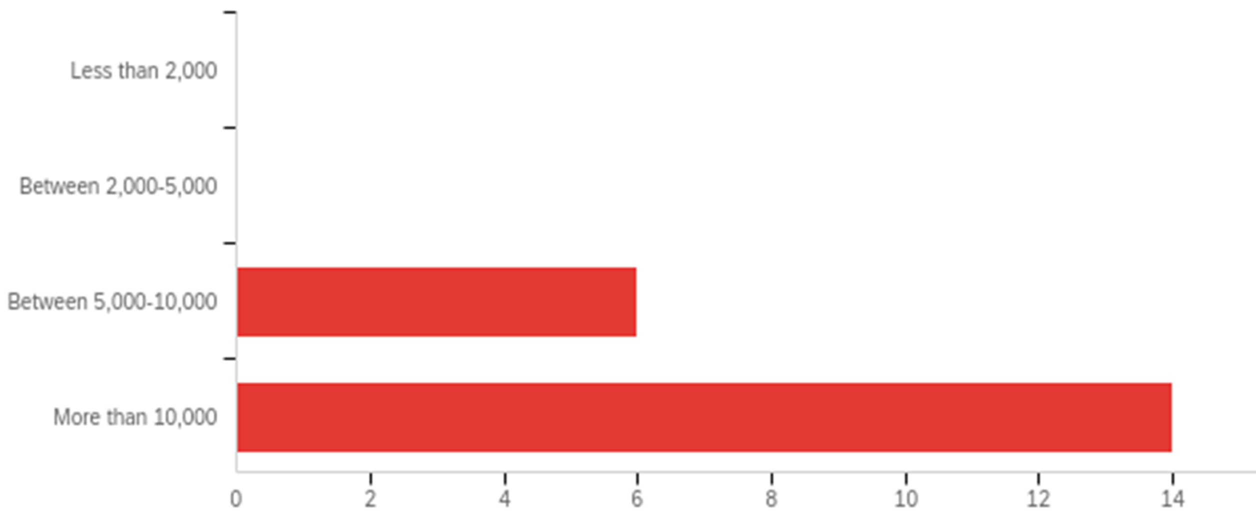


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Is your organization a hospital/ medical facility or not?	1.00	2.00	1.20	0.40	0.16	20

#	Answer	%	Count
1	Yes	80.00%	16
2	No	20.00%	4
	Total	100%	20

Q2 - What is the total square footage of your building (Net area (m2))?

As shown in the Figure below, 70% of the participants are maintenance experts and facility managers of hospital buildings with more than 10,000 m^2 and 30% of the participants are working in hospitals with an area between 5,000 to 10,000 m^2.

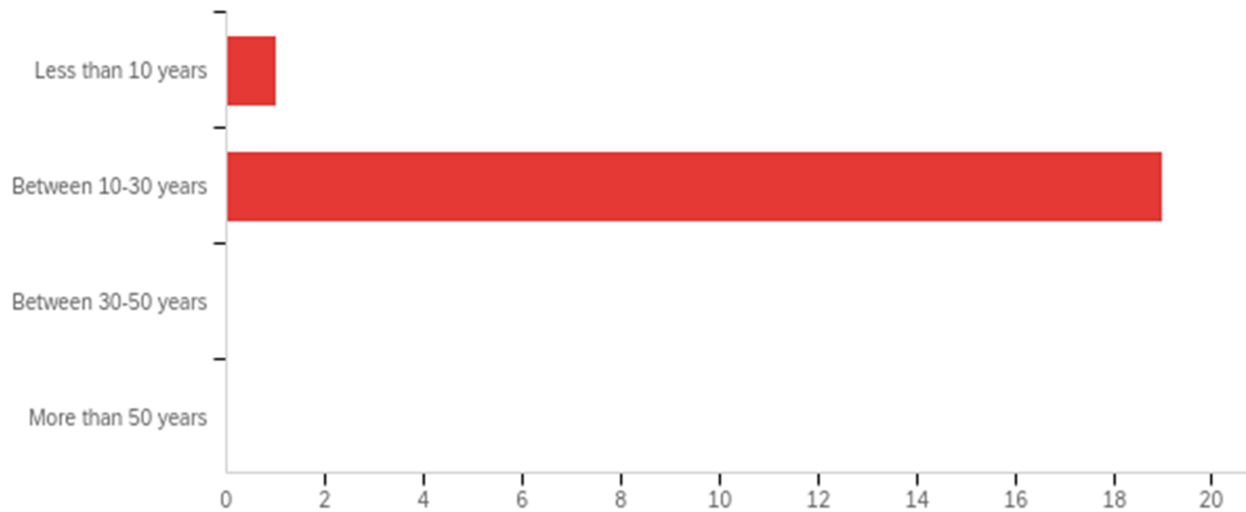


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the total square footage of your building (Net area (m2))?	3.00	4.00	3.70	0.46	0.21	20

#	Answer	%	Count
1	**Less than 2,000**	0.00%	0
2	**Between 2,000-5,000**	0.00%	0
3	**Between 5,000-10,000**	30.00%	6
4	**More than 10,000**	70.00%	14
	Total	100%	20

Q3 - What is the age of your building?

According to the result of this survey, 95% of participants stated that they work in buildings between the ages of 10 to 30.

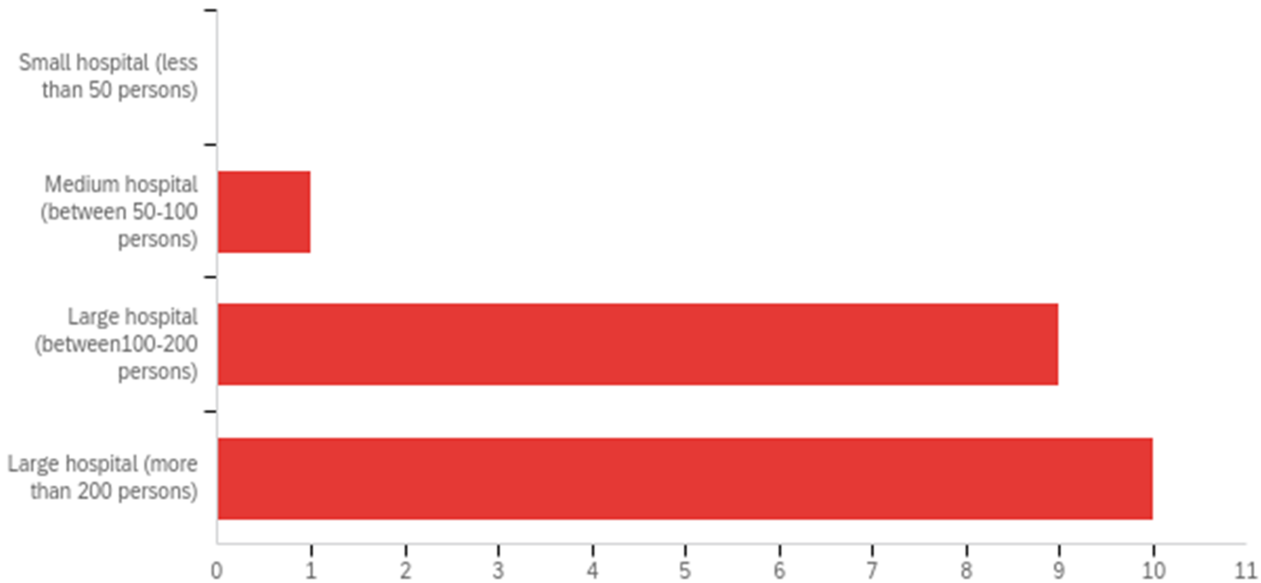


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the age of your building?	1.00	2.00	1.95	0.22	0.05	20

#	Answer	%	Count
1	**Less than 10 years**	5.00%	1
2	**Between 10-30 years**	95.00%	19
3	**Between 30-50 years**	0.00%	0
4	**More than 50 years**	0.00%	0
	Total	100%	20

Q4 - What is the number of visitors of your building per day (including employees)?

As shown in the Figure below, 50% of participants stated that more than 200 persons visit their building daily, 45% of participants stated that between 100 to 200 persons visit their building daily, while only 5% of participants stated that less than 50 persons visit their buildings daily.

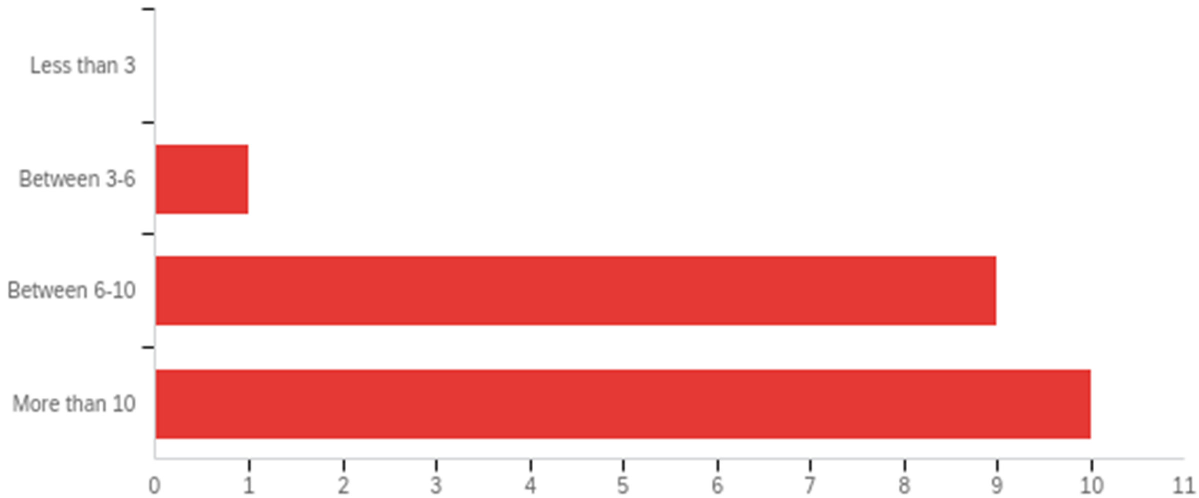


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the number of visitors of your building per day (including employees)?	2.00	4.00	3.45	0.59	0.35	20

#	Answer	%	Count
1	**Small hospital (less than 50 persons)**	0.00%	0
2	**Medium hospital (between 50-100 persons)**	5.00%	1
3	**Large hospital (between100-200 persons)**	45.00%	9
4	**Large hospital (more than 200 persons)**	50.00%	10
	Total	100%	20

Q5 - How many elevators are in the building?

According to the findings of this survey, 50% of participants stated that there were more than 10 elevators in their buildings, 45% of participants stated that there were between 6 to10 elevators in their buildings. In the developed simulation model, it is assumed that there are 10 elevators in the building.

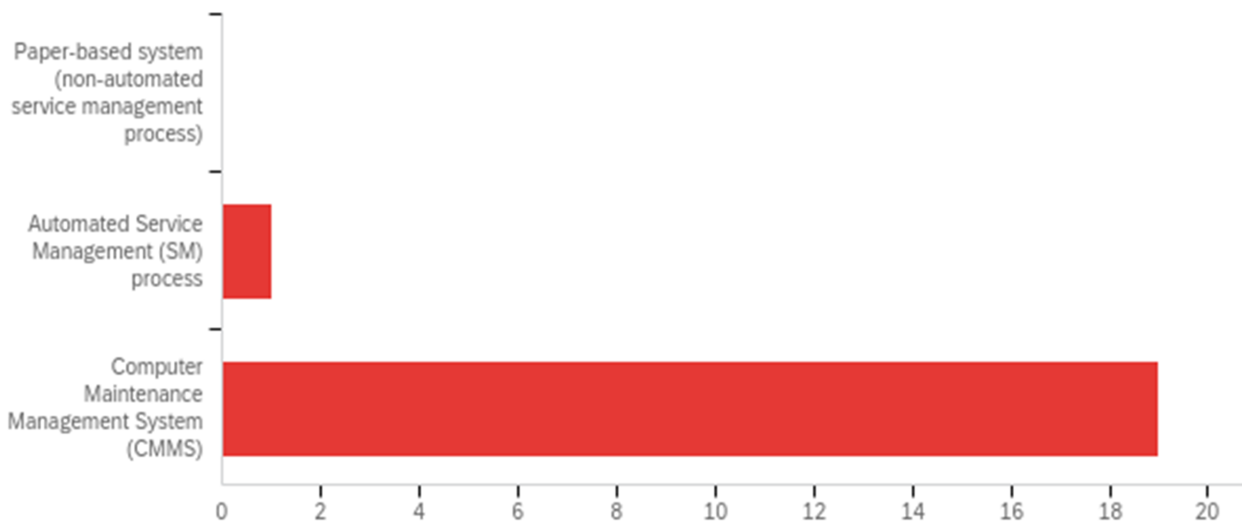


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	How many elevators are in the building?	2.00	4.00	3.45	0.59	0.35	20

#	Answer	%	Count
1	**Less than 3**	0.00%	0
2	**Between 3-6**	5.00%	1
3	**Between 6-10**	45.00%	9
4	**More than 10**	50.00%	10
	Total	100%	20

Q6 - What is the type of maintenance management method in your organization?

The result of this survey revealed that, CMMS is commonly used as a facility information system in participants' buildings.

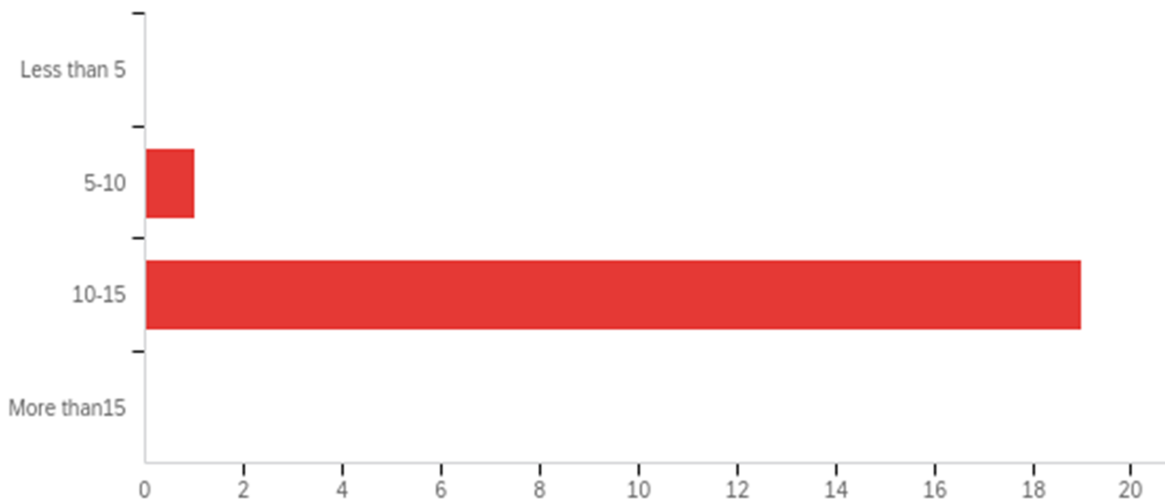


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the type of maintenance management method in your organization?	2.00	3.00	2.95	0.22	0.05	20

#	Answer	%	Count
1	**Paper-based system (non-automated service management process)**	0.00%	0
2	**Automated Service Management (SM) process**	5.00%	1
3	**Computer Maintenance Management System (CMMS)**	95.00%	19
	Total	100%	20

Q7 - <u>How many</u> work orders (e.g., HVAC, Lighting, Elevator) are received per day –on average- due to unexpected failure of the building systems or components? (Number of orders in registration queue).

According to the answers to this question, 95% of participants stated that on average, between 10 and 15 unexpected breakdowns are reported daily in their buildings. This number of orders is assumed as input to the developed DES model. In the developed simulation model, "NewOrderAdmissionPerDay" is considered a dynamic variable that generates orders at specific intervals.

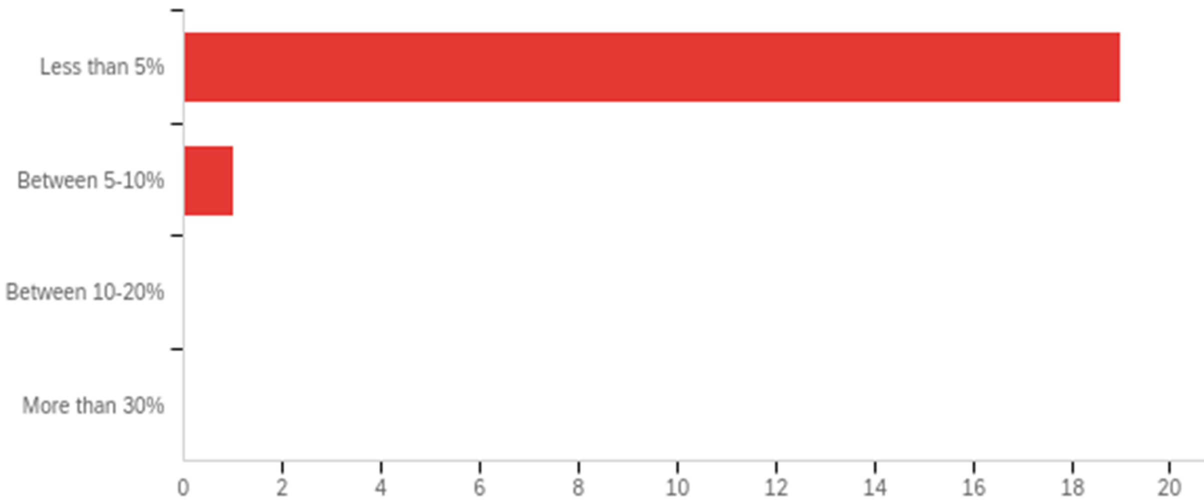


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Number of orders in registration queue	2.00	3.00	2.95	0.22	0.05	20

#	Answer	%	Count
1	**Less than 5**	0.00%	0
2	**5-10**	5.00%	1
3	**10-15**	95.00%	19
4	**More than15**	0.00%	0
	Total	100%	20

Q8 - What is the percentage of rejected work orders (deemed not valid by the inspector)?

As shown in the Figure below, 95 % of participants stated that less than 5% of work orders are rejected in a year. This value is used as the probability of order rejection in simulation models.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the percentage of rejected work orders (deemed not valid by the inspector)?	1.00	2.00	1.05	0.22	0.05	20

#	**Answer**	**%**	**Count**
1	**Less than 5%**	95.00%	19
2	**Between 5-10%**	5.00%	1
3	**Between 10-20%**	0.00%	0
4	**More than 30%**	0.00%	0
	Total	100%	20

Q9 - <u>How often</u>, approximately, FM team receive orders (repair requests) by appropriate authorized personnel per day? (Inter arrival time).

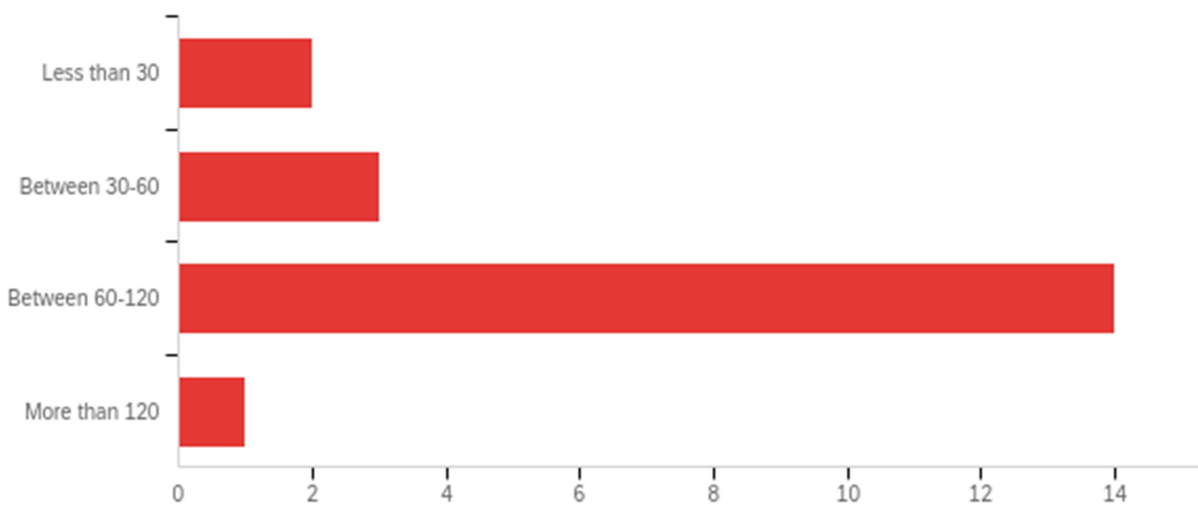
50 % of participants stated that FM team receive orders on average every 4 hours, while 45% of participants stated that FM team receive orders on average every hour. According to the result of this survey, the time between the registration of orders in the simulation model is assumed to be 2 hours.

#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	How often, approximately, facility management team receive orders per day?	1.00	3.00	2.05	0.97	0.95	20

#	Answer	%	Count
1	**Every hour**	45.00%	9
2	**Every 2 hours**	5.00%	1
3	**Every 4 hours**	50.00%	10
4	**Every day**	0.00%	0
	Total	100%	20

Q10 - What is the average <u>waiting time</u> (in minutes) for each order in the registration queue to receive response from the service crew?

As shown in the Figure below, most participants indicated stated that on average, an order waits between 60 to 120 minutes in the registration queue to receive a response from the service crew. Therefore, the parameter of waiting for service crew is defined as an input parameter to the simulation model. The value of this parameter is assumed as a triangular time distribution (0.5, 1, 2) hours.  "WaitingForServiceCrew" is shown as a transition in the simulation model with a timeout value of 2 hours (120 minutes). "WaitingForServiceCrew" *triangular (0.25, 0.5, 1) hours



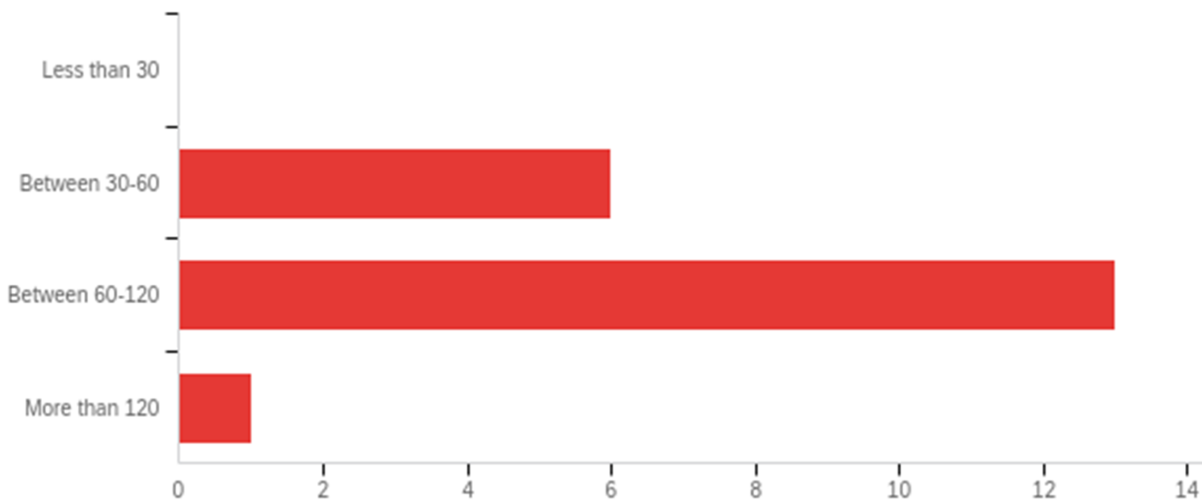
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the average waiting time (in minutes) for each order in the registration queue?	1.00	4.00	2.70	0.71	0.51	20

#	**Answer**	**%**	**Count**
1	Less than 30	10.00%	2
2	Between 30-60	15.00%	3
3	Between 60-120	70.00%	14
4	More than 120	5.00%	1
	Total	100%	20

Q11 - What is the average <u>waiting time</u> (minutes) for each order in the supervision queue to receive responses from the supervisor?

According to the result of this survey, the parameter of waiting for supervisor is defined as an input parameter to the simulation model. The value of this parameter is assumed as a triangular time distribution (0.5, 1, 2) hours.

"ChecksSupervisionQueue" is shown as a transition in the simulation model with a timeout value of 1 hours (60 minutes). "ChecksSupervisionQueue" *triangular (0.5,1,2) hours

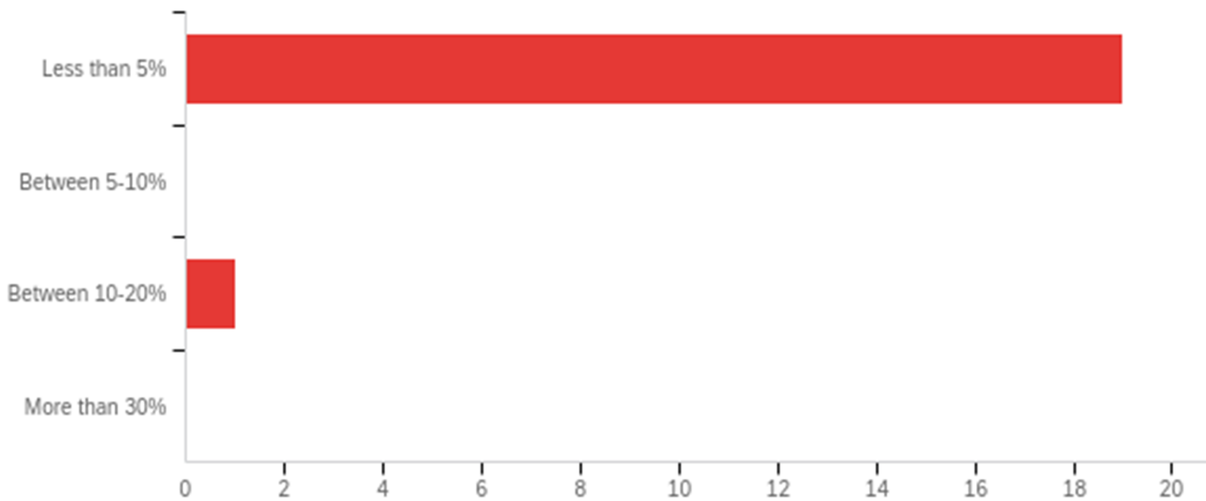


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the average waiting time (minutes) for each order in the supervision queue to receive responses from the supervisor?	2.00	4.00	2.75	0.54	0.29	20

#	Answer	%	Count
1	**Less than 30**	0.00%	0
2	**Between 30-60**	30.00%	6
3	**Between 60-120**	65.00%	13
4	**More than 120**	5.00%	1
	Total	100%	20

Q12 - What percentage of work orders sent back to rework queue?

As shown in the Figure below, 95 % of participants stated that less than 5% of work orders are sent back for rework. This value is used to define the probability of rework in the developed simulation models.

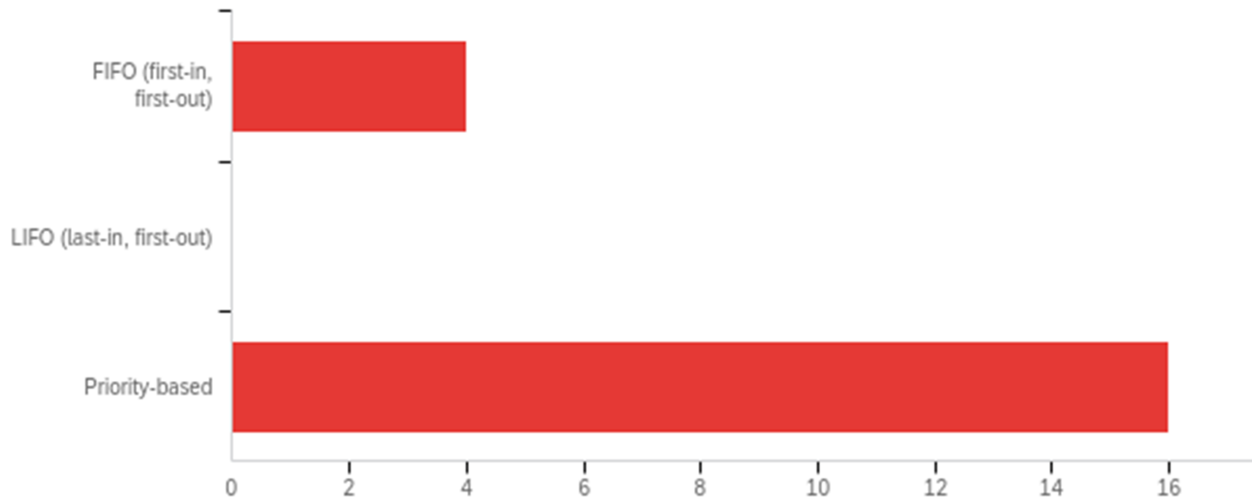


#	What percentage of work orders sent back to rework queue?	Mean
1	What percentage of work orders sent back to rework queue?	1.10

#	Answer	%	Count
1	**Less than 5%**	95.00%	19
2	**Between 5-10%**	0.00%	0
3	**Between 10-20%**	5.00%	1
4	**More than 30%**	0.00%	0
	Total	100%	20

Q13 - How does the facility manager of your organization/hospital arrange orders at execution queue? (What is the queuing discipline?)

According to the survey, 80% of participants stated facility managers prioritize orders for execution, while only 20% of participants mentioned that the orders are arranged based on first-in, first-out. In the developed MARAS model, orders are sorted by priority in the execution queue. Therefore, in the simulation model, a rule is set up that the supervisor-team coordinator agent (TCA) must prioritize orders based on observation and subjective rating.

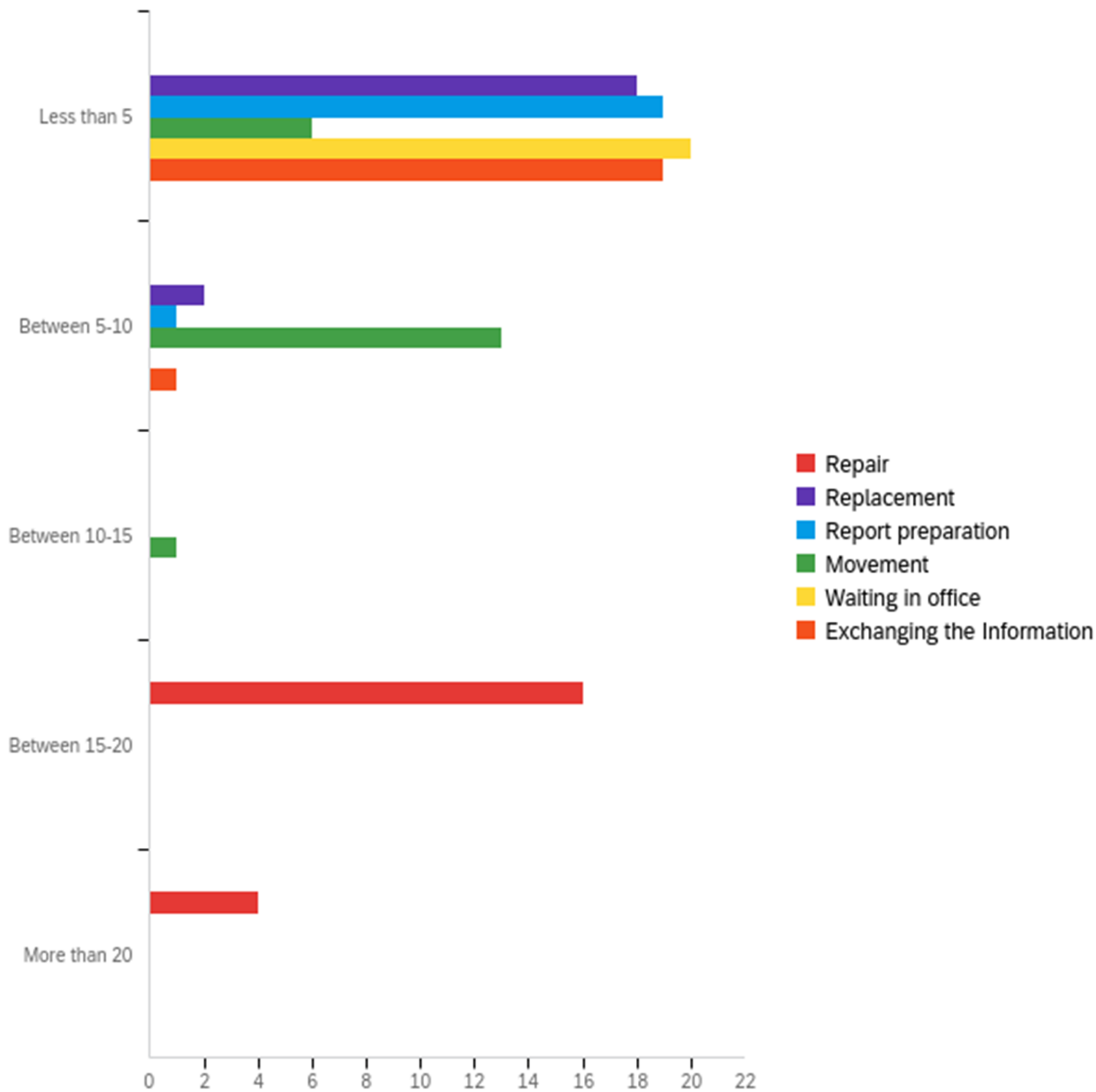


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the queuing discipline in your organization/hospital?	1.00	3.00	2.60	0.80	0.64	20

#	Answer	%	Count
1	**FIFO (first-in, first-out)**	20.00%	4
2	**LIFO (last-in, first-out)**	0.00%	0
3	**Priority-based**	80.00%	16
	Total	100%	20

Q14 - Indicate the total time (in hours) a Corrective Maintenance Resource (CMR)-service crew spends on the following activities in a 40 hours-week?

According to the answers of the survey, a corrective maintenance resource spends 15-20 hours per week working on repairs, less than 5 hours on replacement, less than 5 hours on report preparation, between 5-10 hours on the movement, less than 5 hours waiting for an order in office, and less than 5 hours for information exchange. These values are used to regulate the timing of a corrective maintenance agent (CMA) behaviors in the developed simulation model.

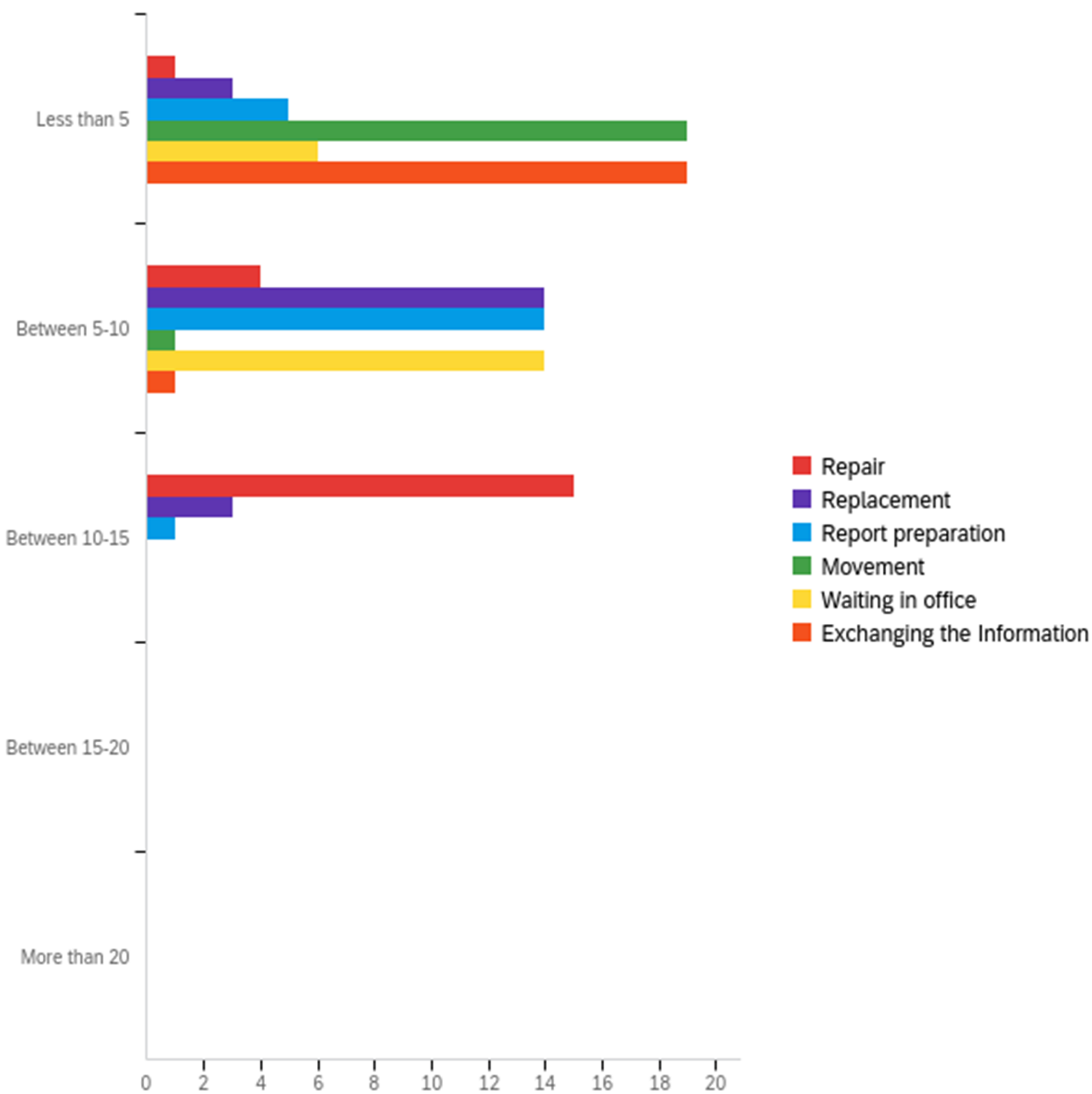


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Repair	4.00	5.00	4.20	0.40	0.16	20
2	Replacement	1.00	2.00	1.10	0.30	0.09	20
3	Report preparation	1.00	2.00	1.05	0.22	0.05	20
4	Movement	1.00	3.00	1.75	0.54	0.29	20
5	Waiting in office	1.00	1.00	1.00	0.00	0.00	20
6	Exchanging the Information	1.00	2.00	1.05	0.22	0.05	20

#	Question	Less than 5		Between 5-10		Between 10-15		Between 15-20		More than 20		Total
1	**Repair**	0.00%	0	0.00%	0	0.00%	0	80.00%	16	20.00%	4	20
2	**Replacement**	90.00%	18	10.00%	2	0.00%	0	0.00%	0	0.00%	0	20
3	**Report preparation**	95.00%	19	5.00%	1	0.00%	0	0.00%	0	0.00%	0	20
4	**Movement**	30.00%	6	65.00%	13	5.00%	1	0.00%	0	0.00%	0	20
5	**Waiting in office**	100.00%	20	0.00%	0	0.00%	0	0.00%	0	0.00%	0	20
6	**Exchanging the Information**	95.00%	19	5.00%	1	0.00%	0	0.00%	0	0.00%	0	20

Q15 - What is the total <u>time</u> (in hours) a Preventive Maintenance Resource (PMR)-service crew spends on the following activities in a 40 hours-week?

As shown in the following Figure, a preventive maintenance resource spends 15-20 hours per week working on repairs, 5-10 hours on replacement, 5-10 hours on report preparation, less than 5 hours on the movement, between 5-10 hours waiting in office, and less than 5 hours for information exchange. These values are used to regulate the timing of a preventive maintenance agent (PMA) behaviors in the developed simulation model.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Repair	1.00	3.00	2.70	0.56	0.31	20
2	Replacement	1.00	3.00	2.00	0.55	0.30	20
3	Report preparation	1.00	3.00	1.80	0.51	0.26	20
4	Movement	1.00	2.00	1.05	0.22	0.05	20
5	Waiting in office	1.00	2.00	1.70	0.46	0.21	20
6	Exchanging the Information	1.00	2.00	1.05	0.22	0.05	20

#	Question	Less than 5		Between 5-10		Between 10-15		Between 15-20		More than 20		Total
1	**Repair**	5.00%	1	20.00%	4	75.00%	15	0.00%	0	0.00%	0	20
2	**Replacement**	15.00%	3	70.00%	14	15.00%	3	0.00%	0	0.00%	0	20
3	**Report preparation**	25.00%	5	70.00%	14	5.00%	1	0.00%	0	0.00%	0	20
4	**Movement**	95.00%	19	5.00%	1	0.00%	0	0.00%	0	0.00%	0	20
5	**Waiting in office**	30.00%	6	70.00%	14	0.00%	0	0.00%	0	0.00%	0	20
6	**Exchanging the Information**	95.00%	19	5.00%	1	0.00%	0	0.00%	0	0.00%	0	20

Appendix D: Survey Questionnaire- Part 2

EVALUATION OF THE CURRENT RESOURCE ALLOCATION PLAN

6) Elevator Operation and Maintenance Information

Service management (SM) sub process includes "Registration", "Planning and Resource allocation", "Executing", and "Supervision and Documentation".

Q16) Indicate the approximate time spent in the following sub-processes for elevator failure (per hours)

SM sub process	Time required in hours			
	Less than 1	Between 1-2	Between 2-3	More than 3
Registration	☐	☐	☐	☐
Planning and Resource allocation	☐	☐	☐	☐
Executing	☐	☐	☐	☐
Supervision and Documentation	☐	☐	☐	☐

Q17) What is the approximate age (per years) of the elevators in your building?

Less than 5	☒	5-10	☐	10-20	☐	20-25	☐	More than 25	☐
Other (please specify ………………………………………………………………..……….)									

Q18) How often elevators are breaking down on average (mean time between failures)?

Every week	☐	Every 2 weeks	☐	Every month	☐	Every 3 months	☐	Every 6 months	☐
Other (please specify ……………………………………………………………..…...……….)									

Q19) How long does it take approximately to repair an elevator (average repair time per hours)?

Note that this time does not include the time of rework due to the rejected work.

Less than one	☐	Between 1-2	☐	Between 2-3	☐	More than 3	☐

Other (please specify…………………………………………………………….…….………….)

Q20) How often the elevators are checked up based on the maintenance schedule? the services are performed by in-house personnel or contractors?

	Planned Maintenance Period	In-house	Contractor	Purposes
☐	Monthly	☐	☐	…………………………………….
☐	Every 3 months	☐	☐	…………………………………….
☐	Every 6 months	☐	☐	…………………………………….
☐	Annually	☐	☐	…………………………………….
☐	Every five years	☐	☐	…………………………………….
Other (please specify ………………………………………………………..…..……….)				

Q21) What are the decision criteria for elevator replacement?

Age of elevator	☐	Number of repair	☐	Number of maintenance interventions	☐	Maintenance cost	☐
Other (please specify ……………………………………………………………..…………)							

Q22) What percentage of work orders within a year are related to repair of the elevators?

Less than 10	☐	Between 10-20	☐	Between 20-30	☐	More than 30	☐
Other (please specify ……………………………………………………………..…………)							

Q23) What percentage of work orders within a year are related to preventive maintenance of the elevators?

Less than 10	☐	Between 10-20	☐	Between 20-30	☐	More than 30	☐
Other (please specify ……………………………………………………………..…………)							

Q24) What is <u>the average reworked</u> time spent on repair of an <u>elevator</u> (per hours)?

Less than one	☐	Between 1-2	☐	Between 2-3	☐	More than 3	☐
Other (please specify …………………………………………………………..………….)							

7) Resource Allocation Assessment

Q25) Please indicate the percentage of the <u>corrective maintenance activities</u> (repair and replacement) performed by <u>in-house</u> personnel for elevators?

	Less than 25%	Between 25%-50%	Between 50%-75%	More than 75%
Repair	☐	☐	☐	☐
Replacement	☐	☐	☐	☐

Q26) Please indicate the <u>percentage</u> of the <u>preventive maintenance activities</u>, which are done by <u>in-house</u> personnel for elevators?

	Less than 25%	Between 25-50%	Between 50-75%	More than 75%
Repair	☐	☐	☐	☐
Replacement	☐	☐	☐	☐

Q27) What is the <u>number of service crews used</u> for elevator repairs or maintenance?

Resource name	Less than 2	Between 2-5	Between 5-7	More than 7
Administration	☐	☐	☐	☐
Facility manager	☐	☐	☐	☐
Supervisor	☐	☐	☐	☐
Corrective resource	☐	☐	☐	☐
Maintenance resource	☐	☐	☐	☐
Outsourced to Contractor	☐	☐	☐	☐

Q28) What is the number of hours, on average, spent by service crews for elevators repair or maintenance?

Resource name	Less than one	Between 1- 2	Between 2-3	More than 3
Administration	☐	☐	☐	☐
Facility manager	☐	☐	☐	☐
Supervisor	☐	☐	☐	☐
Corrective resource	☐	☐	☐	☐
Maintenance resource	☐	☐	☐	☐
Contractor	☐	☐	☐	☐

Q29) Indicate the total time (in hours) a supervisor spends on the following activities in a period of 40 hours-week?

	Less than 5	Between 5-10	Between 10-15	Between 15-20	More than 20
Inspection	☐	☐	☐	☐	☐
Verification (Damage examination)	☐	☐	☐	☐	☐
Prioritization	☐	☐	☐	☐	☐
Supervision	☐	☐	☐	☐	☐
Report preparation	☐	☐	☐	☐	☐
Movement	☐	☐	☐	☐	☐
Waiting in office	☐	☐	☐	☐	☐
Exchanging Information	☐	☐	☐	☐	☐

Q30) Please indicate the Risk Priority (likelihood of occurrence, likelihood of detection, and severity of impact) for elevator failure.

	Low	Medium	High
Risk Priority for elevator failure	☐	☐	☐

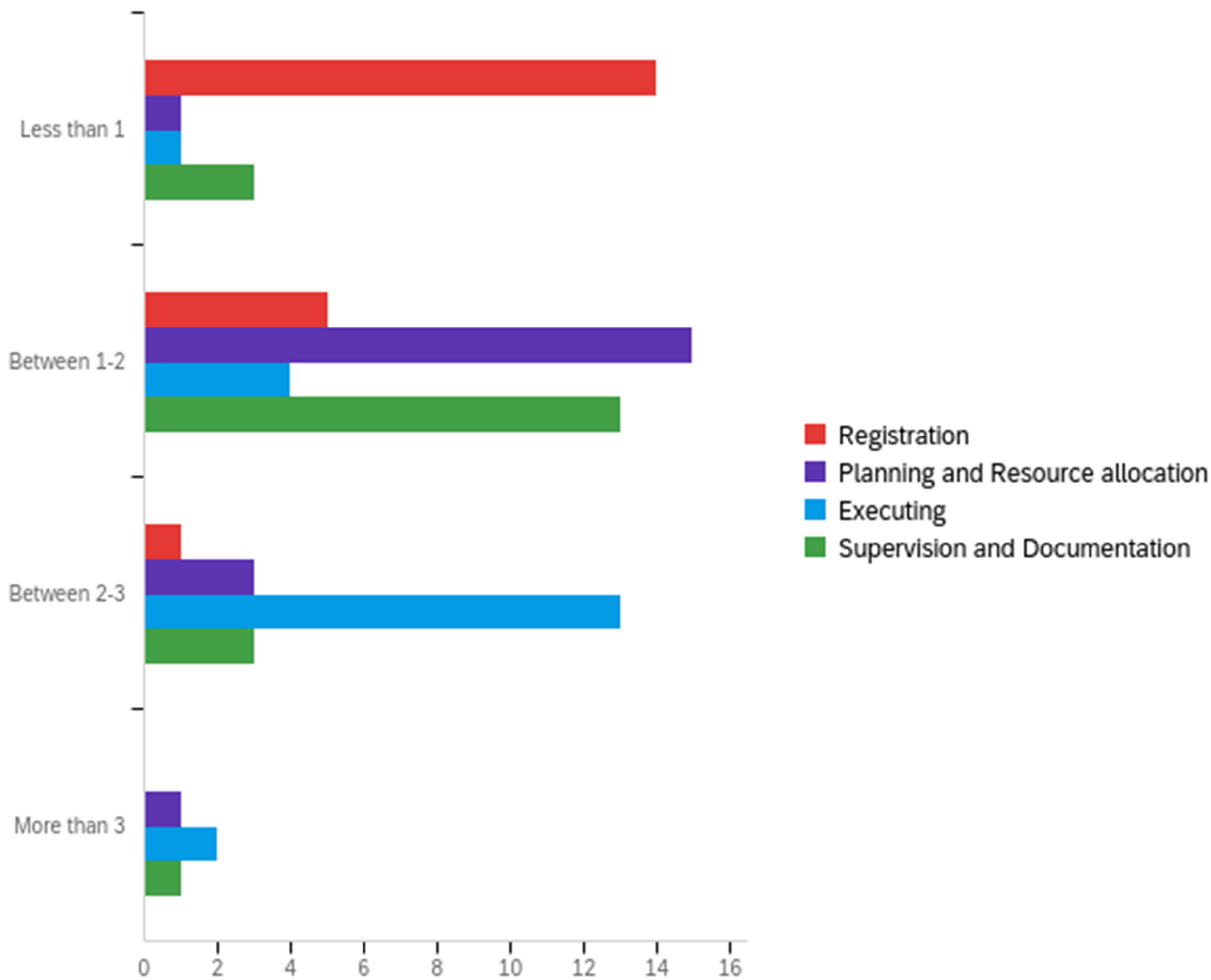
The survey (Part 2) was hosted on:

https://qfreeaccountssjc1.az1.qualtrics.com/jfe/form/SV_6GB34kCINpJ4veR

Appendix E: Survey Results Analysis and Discussion- Part 2

Q16 - Indicate the approximate <u>time</u> spent in the following sub-processes for elevator failure (per hours). Note: Service management (SM) sub process includes "Registration", "Planning and Resource allocation", "Executing", and "Supervision and Documentation".

According to analyze the results, the registration of the elevators takes less than 1 hour, the planning and resource allocation takes between 1-2 hours, the execution takes between 2-3 hours, and finally the supervision and documentation takes between 1-2 hours. These values are used as the input parameters in the developed DES model.

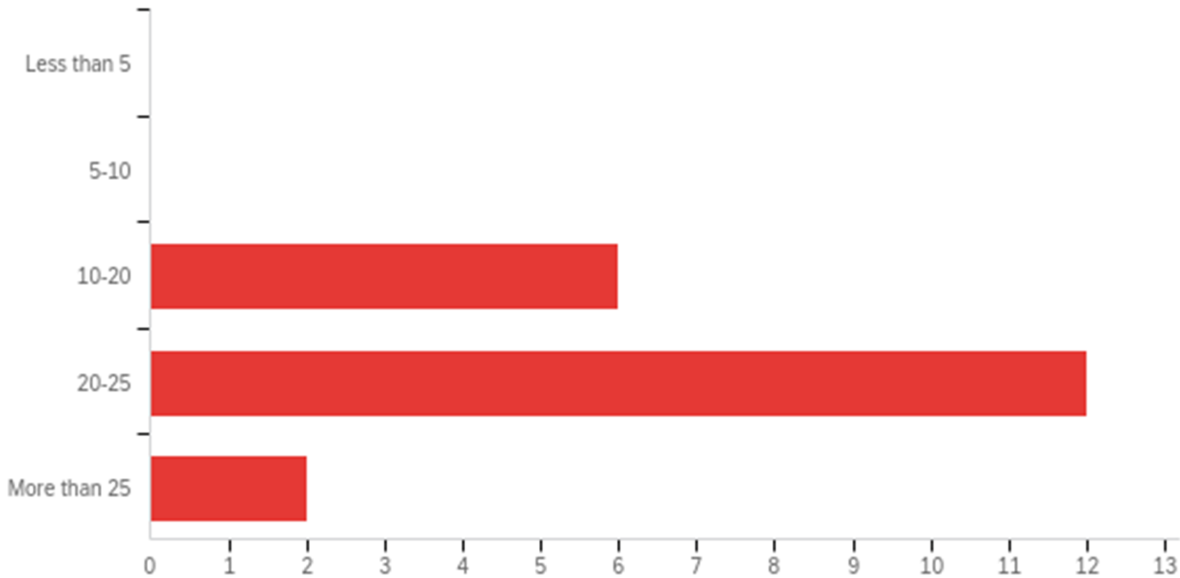


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Registration	1.00	3.00	1.35	0.57	0.33	20
2	Planning and Resource allocation	1.00	4.00	2.20	0.60	0.36	20
3	Executing	1.00	4.00	2.80	0.68	0.46	20
4	Supervision and Documentation	1.00	4.00	2.10	0.70	0.49	20

#	Question	Less than 1		Between 1-2		Between 2-3		More than 3		Total
1	**Registration**	70.00%	14	25.00%	5	5.00%	1	0.00%	0	20
2	**Planning and Resource allocation**	5.00%	1	75.00%	15	15.00%	3	5.00%	1	20
3	**Executing**	5.00%	1	20.00%	4	65.00%	13	10.00%	2	20
4	**Supervision and Documentation**	15.00%	3	65.00%	13	15.00%	3	5.00%	1	20

Q17 - What is the approximate age (per years) of the elevators in your building?

According to the results, 60% of the participants stated that the average age of the elevator in their building was between 20-25 years, 30% stated that the average age was between 10 and 20 years, and 10% stated that the average age was over 25 years.

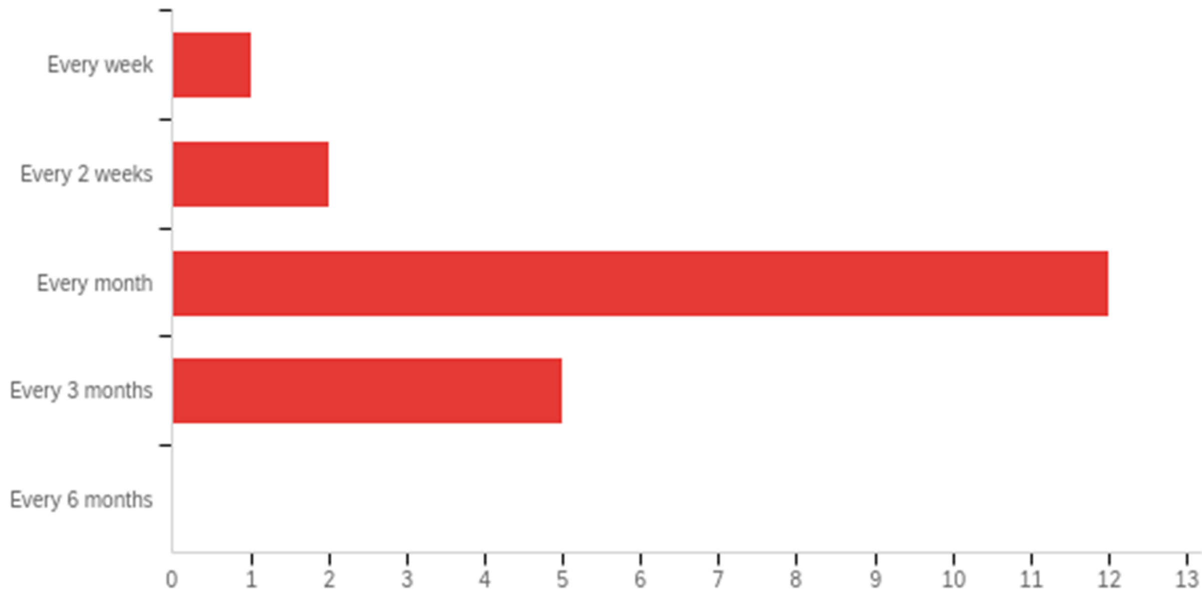


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the approximate age (per years) of the elevators in your building?	3.00	5.00	3.80	0.60	0.36	20

#	Answer	%	Count
1	**Less than 5**	0.00%	0
2	**5-10**	0.00%	0
3	**10-20**	30.00%	6
4	**20-25**	60.00%	12
5	**More than 25**	10.00%	2
	Total	100%	20

Q18 - How often elevators are breaking down on average (mean time between failures)?

According to these results, 60% of the participants stated that the mean time between failures (MTBF) of the elevators is 30 days, while 25% of the participants stated a period of three months. In the simulation model MTBF is used to adjust the failure rate of the elevators.

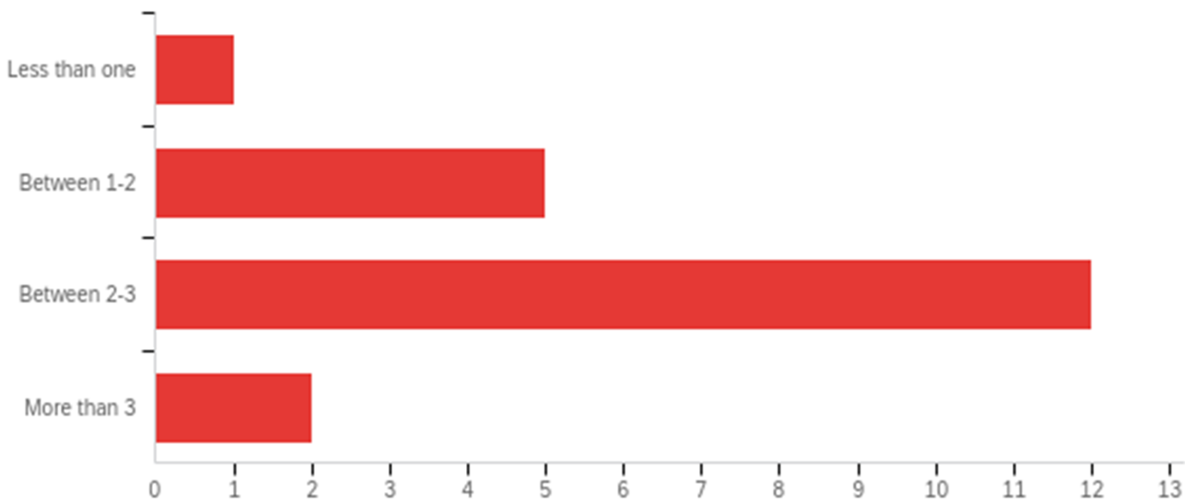


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	How often elevators are breaking down on average (mean time between failures)?	1.00	4.00	3.05	0.74	0.55	20

#	Answer	%	Count
1	**Every week**	5.00%	1
2	**Every 2 weeks**	10.00%	2
3	**Every month**	60.00%	12
4	**Every 3 months**	25.00%	5
5	**Every 6 months**	0.00%	0
	Total	100%	20

Q19 - <u>How long</u> does it take approximately to repair an elevator (average repair time per hours)? Note that this time does not include the time of rework due to the rejected work.

As shown in the following Figure, 60% of the participants stated that the average repair time of an elevator is between 2-3 hours, while 25% of the participants indicated a range of 1 to 2 hours. This value is used as the input parameter RepairTime in the developed simulation model.

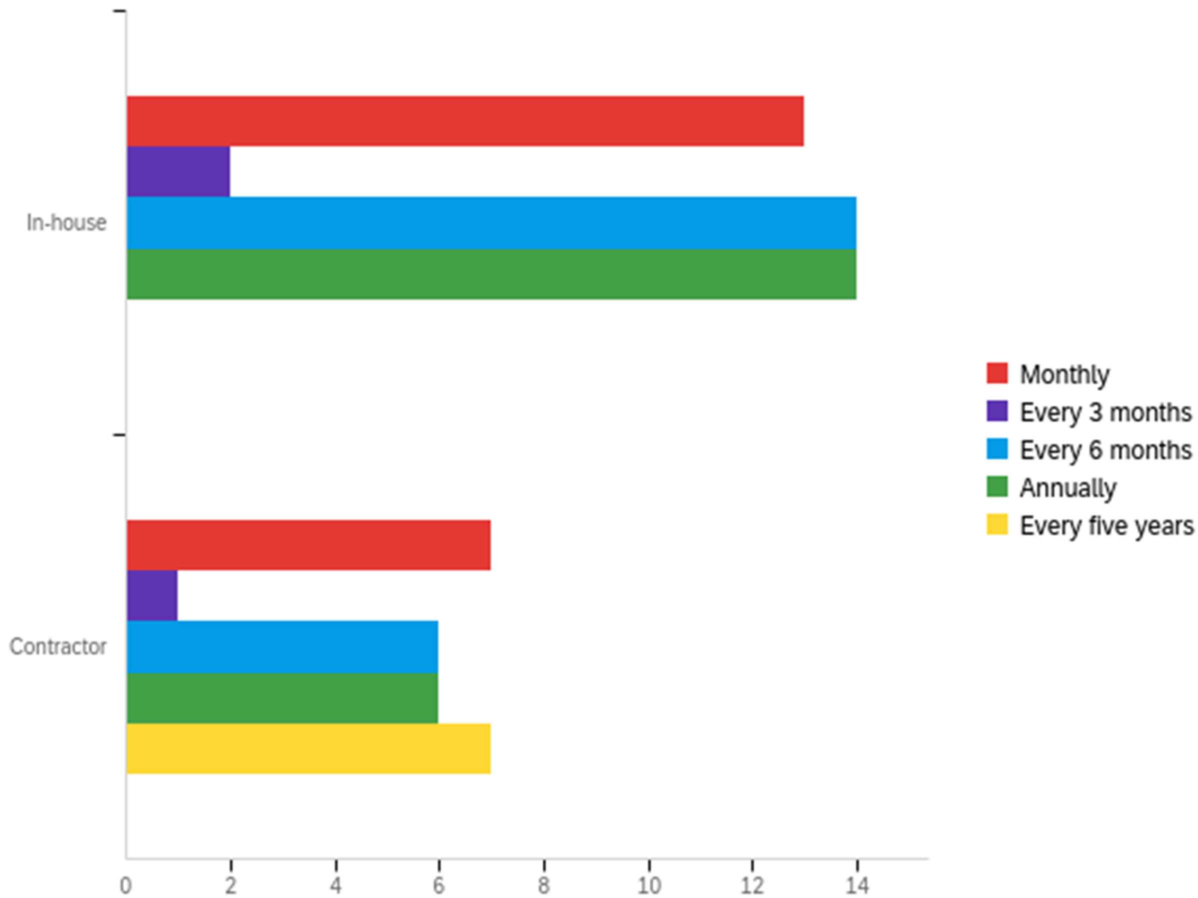


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	How long does it take approximately to repair an elevator (average repair time per hours)? Note that this time does not include the time of rework due to the rejected work.	1.00	4.00	2.75	0.70	0.49	20

#	Answer	%	Count
1	**Less than one**	5.00%	1
2	**Between 1-2**	25.00%	5
3	**Between 2-3**	60.00%	12
4	**More than 3**	10.00%	2
	Total	100%	20

Q20 - <u>How often</u> the elevators are checked up based on the maintenance schedule? the services are performed by in-house personnel or contractors?

As shown in the Figure below, it is indicated that the elevator components should be inspected monthly, every six months, and annually. These maintenance intervals are used to define preventive maintenance schedule of elevators in the simulation model.

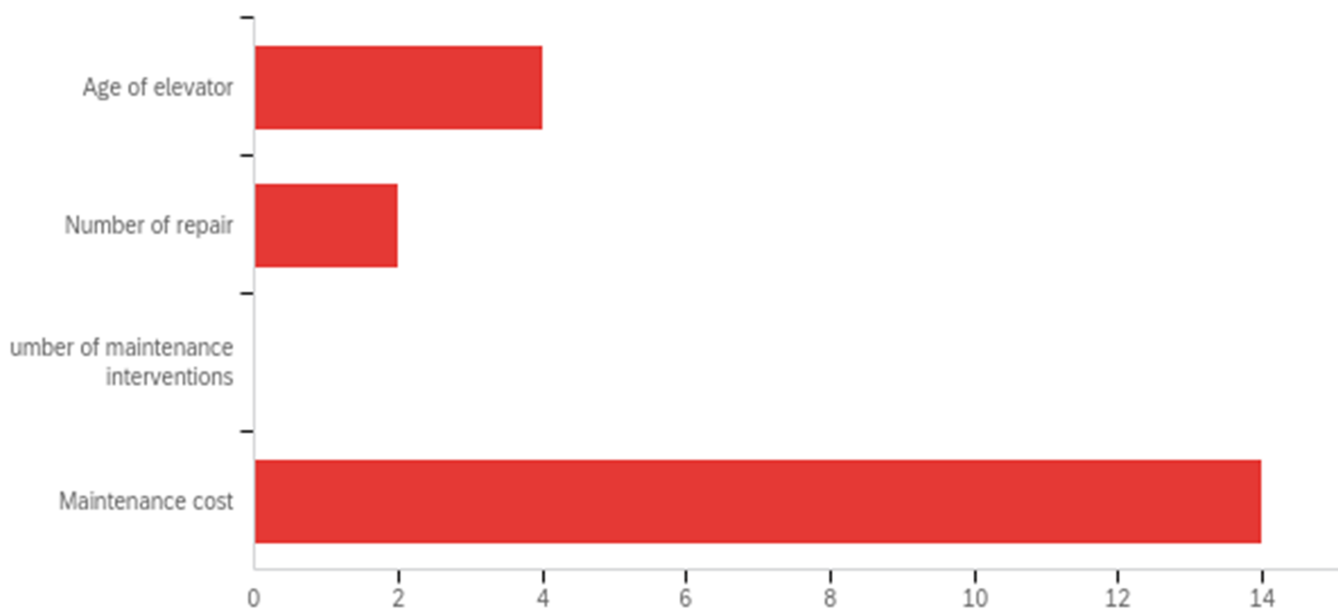


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Monthly	1.00	2.00	1.35	0.48	0.23	20
2	Every 3 months	1.00	2.00	1.33	0.47	0.22	3
3	Every 6 months	1.00	2.00	1.30	0.46	0.21	20
4	Annually	1.00	2.00	1.30	0.46	0.21	20
5	Every five years	2.00	2.00	2.00	0.00	0.00	7

#	Question	In-house		Contractor		Total
1	**Monthly**	65.00%	13	35.00%	7	20
2	**Every 3 months**	66.67%	2	33.33%	1	3
3	**Every 6 months**	70.00%	14	30.00%	6	20
4	**Annually**	70.00%	14	30.00%	6	20
5	**Every five years**	0.00%	0	100.00%	7	7

Q21 - What are the <u>decision criteria</u> for elevator replacement?

The findings of this questions are used to determine the replacement policy for the simulation model. According to these results, cost analysis is the main factor in replacing building components, but since the economic aspects of maintenance (beyond the scope of this research) are not considered in the developed model, the age of building components, number of repairs, and the performance conditions, are defined as the decision criteria for replacing building components.

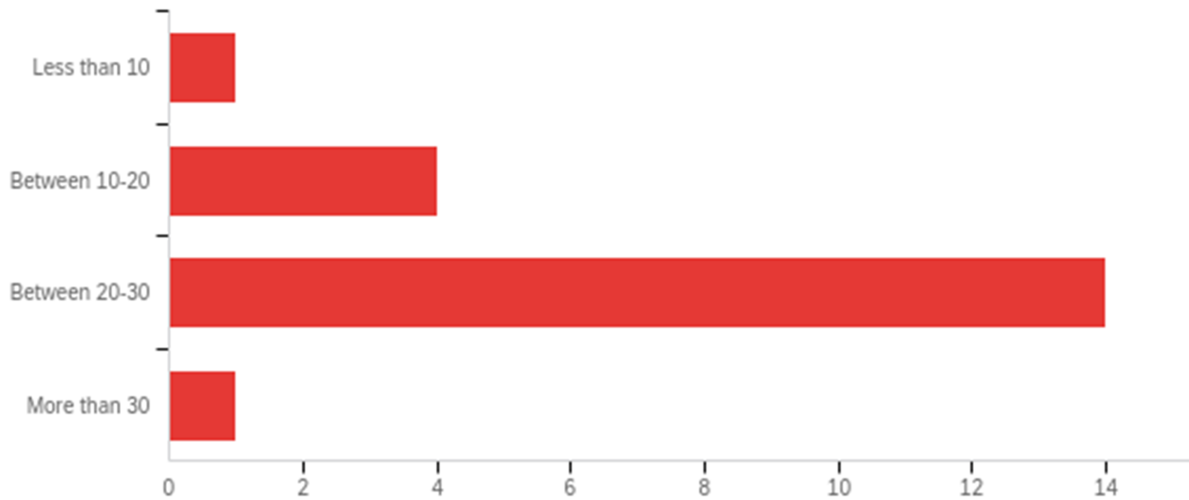


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What are the decision criteria for elevator replacement?	1.00	4.00	3.20	1.25	1.56	20

#	Answer	%	Count
1	**Age of elevator**	20.00%	4
2	**Number of repair**	10.00%	2
3	**Number of maintenance interventions**	0.00%	0
4	**Maintenance cost**	70.00%	14
	Total	100%	20

Q22 - What percentage of work orders within a year are related to repair of the elevators?

As shown by the results of this survey, 70% of participants stated that between 20 to 30 percentages of work orders per year are related to elevator repair. Therefore, the elevators of a hospital are selected as the building component agents (BCAs) and their functions and maintenance behaviors are simulated.

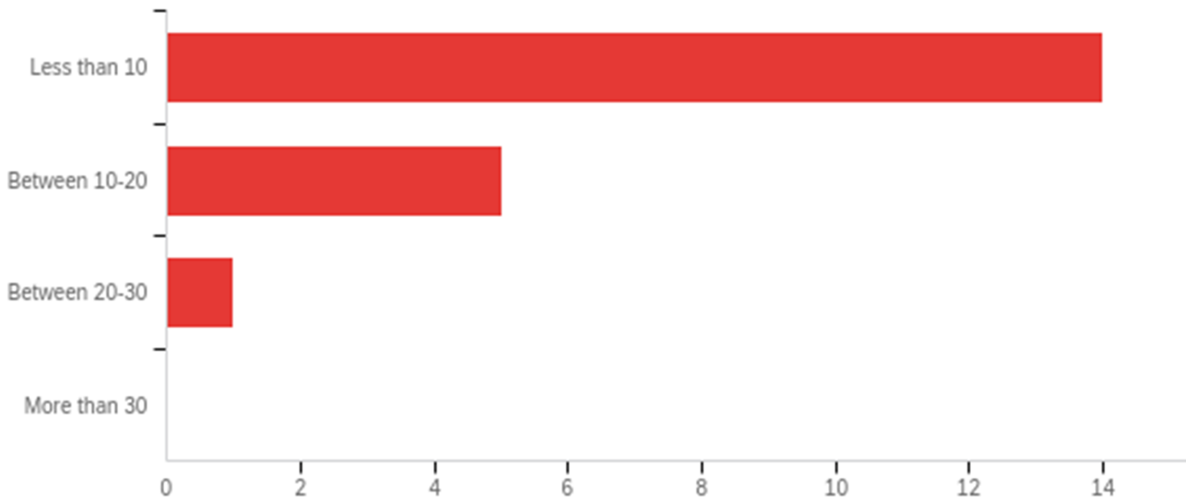


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What percentage of work orders within a year are related to repair of the elevators?	1.00	4.00	2.75	0.62	0.39	20

#	Answer	%	Count
1	**Less than 10**	5.00%	1
2	**Between 10-20**	20.00%	4
3	**Between 20-30**	70.00%	14
4	**More than 30**	5.00%	1
	Total	100%	20

Q23 - What percentage of work orders within a year are related to preventive maintenance of the elevators?

According to these results, 70% of participants stated that orders for elevator preventive maintenance per year are less than 10%, while 25% of participants stated the orders are between 10 to 20 %. So, a small number of service crews are dedicated to preventive maintenance activities of elevators. This value is used to determine the number of preventive maintenance agents (PMAs) in the resource pool of the developed simulation models.

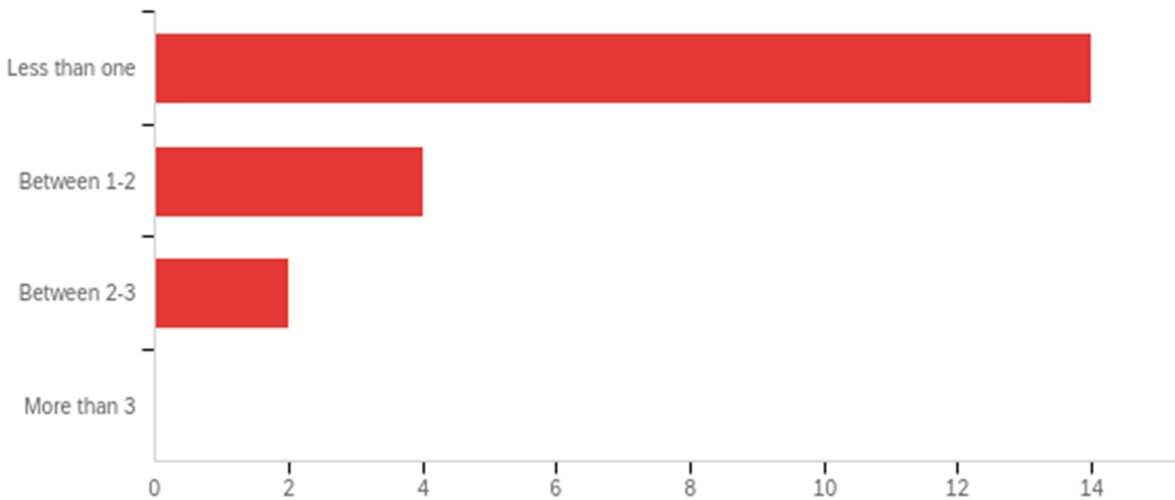


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What percentage of work orders within a year are related to preventive maintenance of the elevators?	1.00	3.00	1.35	0.57	0.33	20

#	Answer	%	Count
1	**Less than 10**	70.00%	14
2	**Between 10-20**	25.00%	5
3	**Between 20-30**	5.00%	1
4	**More than 30**	0.00%	0
	Total	100%	20

Q24 - What is the average reworked time spent on repair of an elevator (per hours)?

70% of participants stated that the average rework/ repair time of the elevators is less than 1 hour. This value is used to determine the rework/ repair time parameter in the developed simulation models.

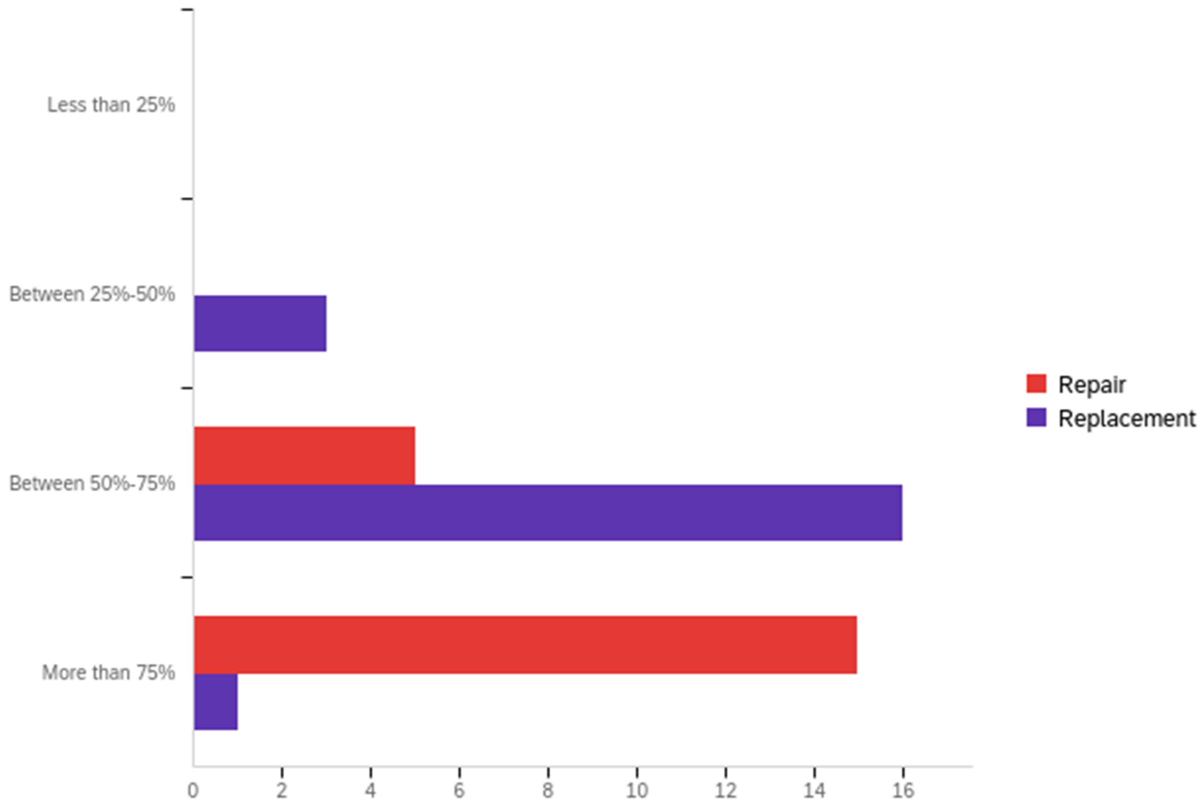


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	What is the average reworked time spent on repair of an elevator (per hours)?	1.00	3.00	1.40	0.66	0.44	20

#	Answer	%	Count
1	**Less than one**	70.00%	14
2	**Between 1-2**	20.00%	4
3	**Between 2-3**	10.00%	2
4	**More than 3**	0.00%	0
	Total	100%	20

Q25 - Please indicate the percentage of the corrective maintenance activities (repair and replacement) performed by in-house personnel for elevators?

According to these results, more than 75% of elevator repair activities and 50%-75% of elevator replacement activities are performed by in-house resources. Therefore, in-house resources information is used to develop and implement the simulation model for resource allocation.

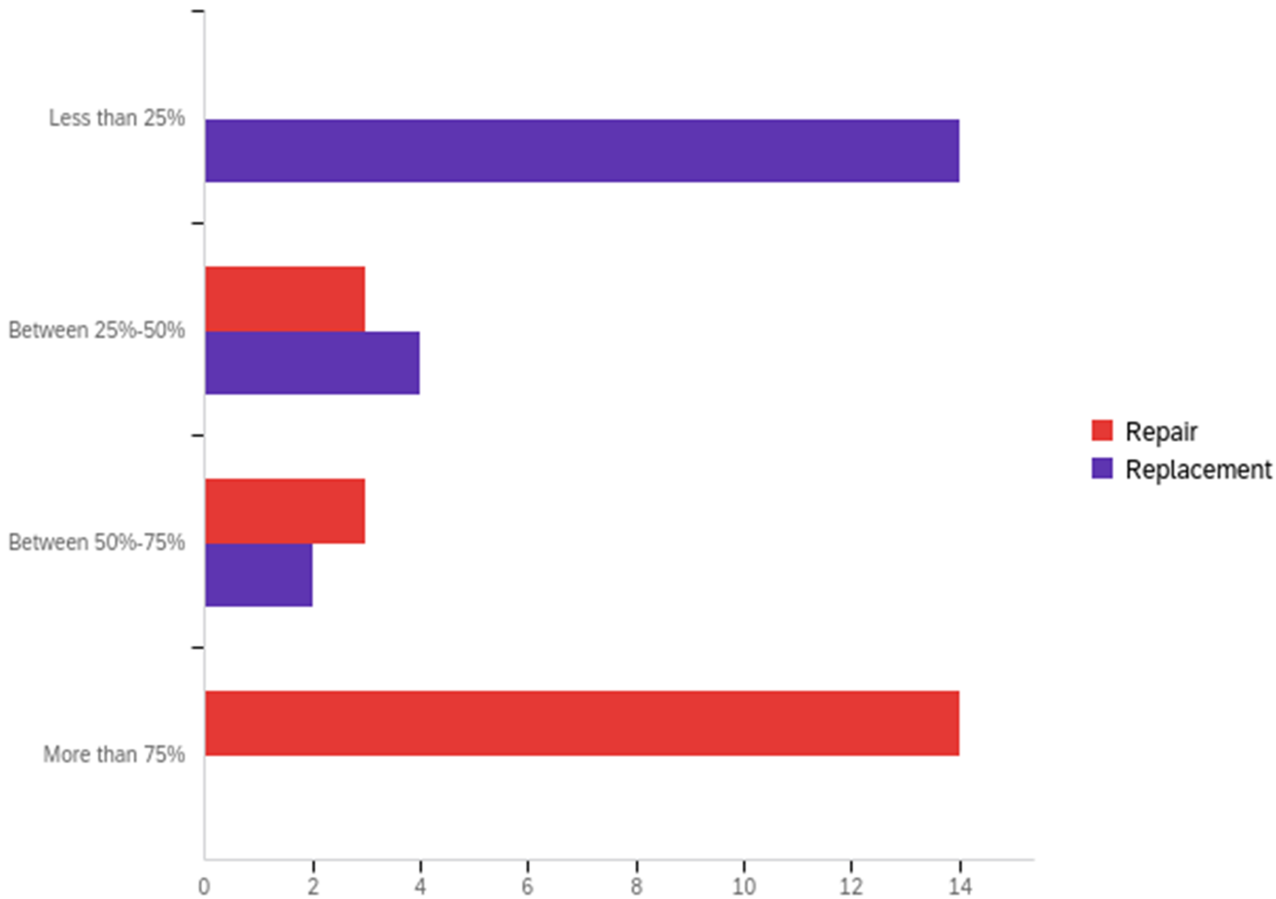


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Repair	3.00	4.00	3.75	0.43	0.19	20
2	Replacement	2.00	4.00	2.90	0.44	0.19	20

#	Question	Less than 25%		Between 25%-50%		Between 50%-75%		More than 75%		Total
1	**Repair**	0.00%	0	0.00%	0	25.00%	5	75.00%	15	20
2	**Replacement**	0.00%	0	15.00%	3	80.00%	16	5.00%	1	20

Q26 - Please indicate the percentage of the preventive maintenance activities, which are done by in-house personnel for elevators?

70% of participants of this survey stated that more than 75% of the elevator routine maintenance activities are performed by in-house resources, while 70% of them stated that, less than 25% of the elevators are replaced by in-house personnel. Therefore, in-house resources information is used to develop and implement the simulation model for resource allocation.

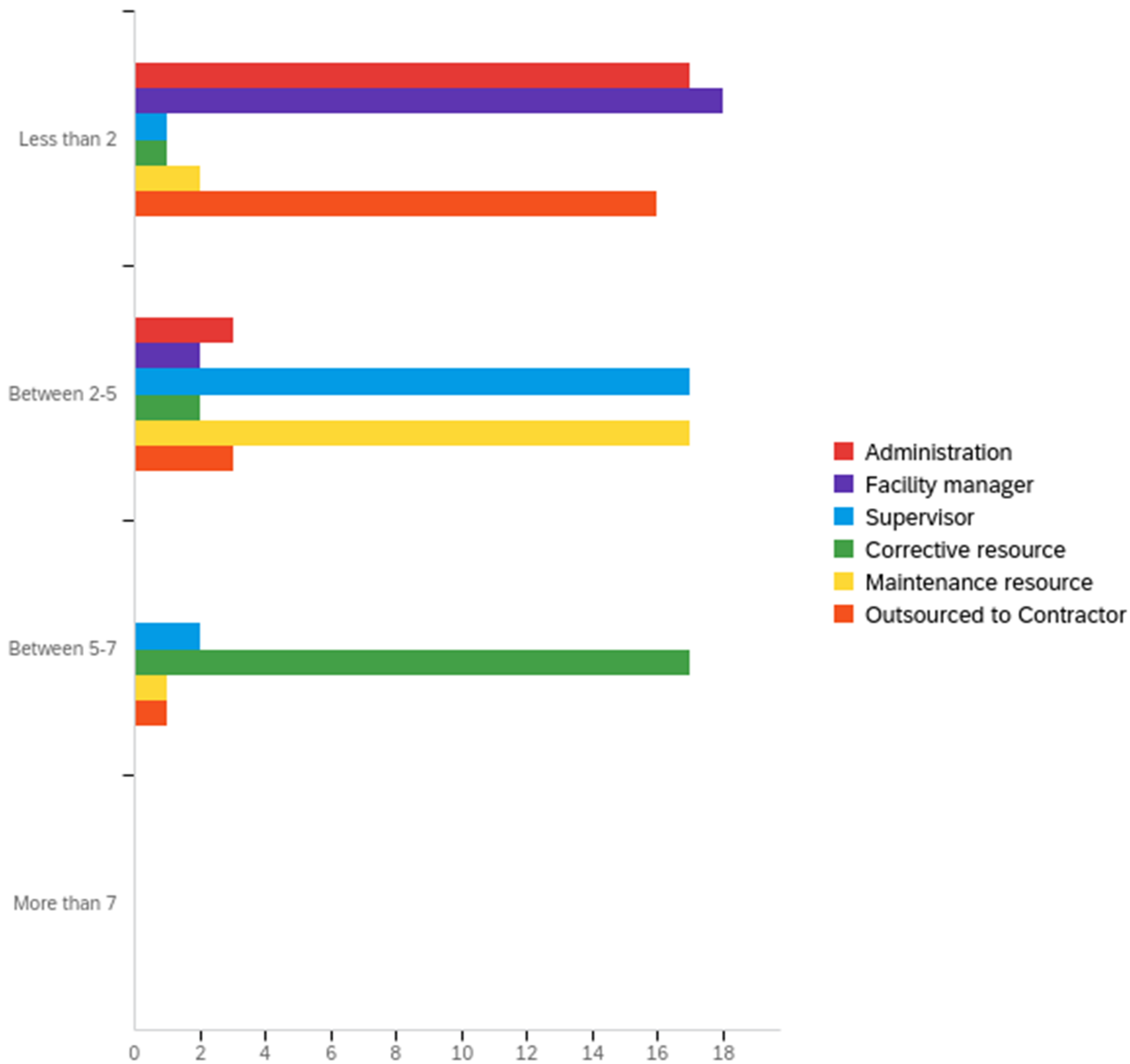


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Repair	2.00	4.00	3.55	0.74	0.55	20
2	Replacement	1.00	3.00	1.40	0.66	0.44	20

#	Question	Less than 25%		Between 25%-50%		Between 50%-75%		More than 75%		Total
1	**Repair**	0.00%	0	15.00%	3	15.00%	3	70.00%	14	20
2	**Replacement**	70.00%	14	20.00%	4	10.00%	2	0.00%	0	20

Q27- What is the <u>number of service crews</u> used for elevator repairs or maintenance?

85% of participants indicated that less than 3 service crews for administrative and contracting affairs, between 3 to 5 supervisors and maintenance resources, and between 5 to 7 crews for corrective maintenance are required for elevator maintenance. In addition, 90% of the participants indicated that less than 3 facility managers are also needed. To simulate resource allocation for elevator maintenance, it is assumed that there are 1 resource for administration, 1 facility managers, between 3 to 5 supervisors, between 5 to 7 corrective maintenance resources, and 3 to 5 preventive maintenance resources in the resource pool.

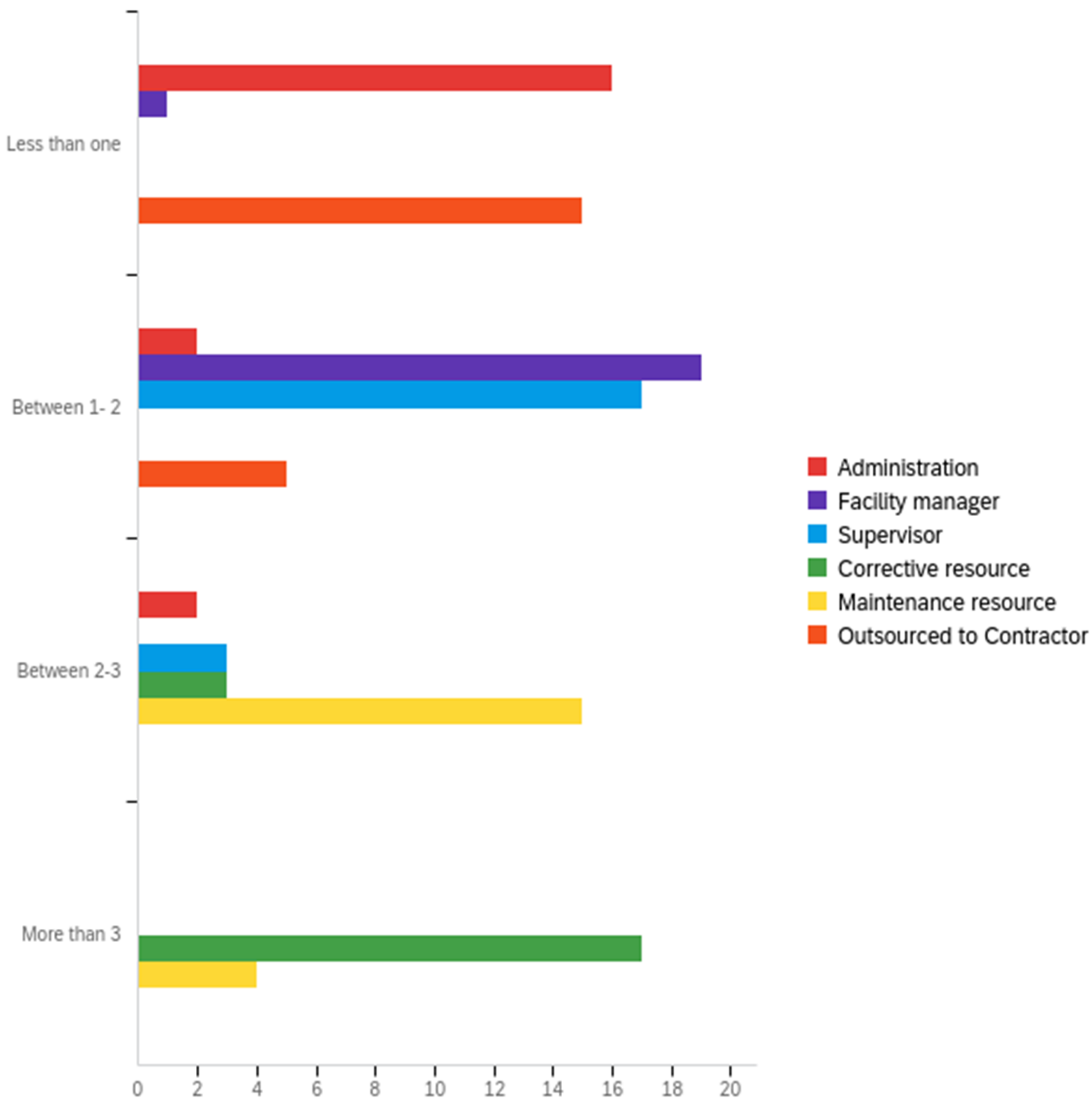


#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Administration	1.00	2.00	1.15	0.36	0.13	20
2	Facility manager	1.00	2.00	1.10	0.30	0.09	20
3	Supervisor	1.00	3.00	2.05	0.38	0.15	20
4	Corrective resource	1.00	3.00	2.80	0.51	0.26	20
5	Maintenance resource	1.00	3.00	1.95	0.38	0.15	20
6	Outsourced to Contractor	1.00	3.00	1.25	0.54	0.29	20

#	Question	Less than 3		Between 3-5		Between 5-7		More than 7		Total
1	**Administration**	85.00%	17	15.00%	3	0.00%	0	0.00%	0	20
2	**Facility manager**	90.00%	18	10.00%	2	0.00%	0	0.00%	0	20
3	**Supervisor**	5.00%	1	85.00%	17	10.00%	2	0.00%	0	20
4	**Corrective resource**	5.00%	1	10.00%	2	85.00%	17	0.00%	0	20
5	**Maintenance resource**	10.00%	2	85.00%	17	5.00%	1	0.00%	0	20
6	**Outsourced to Contractor**	80.00%	16	15.00%	3	5.00%	1	0.00%	0	20

Q28 - What is the <u>number of hours</u>, on average, spent by <u>service crews</u> for elevators repair or maintenance?

80% of the participants stated that it takes less than 2 hours to register the elevator failure in the system, 95% of the participants stated that a facility manager spends 2 to 3 hours planning and allocating resources for the elevator failure, 85 ٪ participants stated that a supervisor spends 2 to 3 hours and a corrective maintenance resource spends more than 5 hours repairing an elevator, 75% of participants stated that a preventive maintenance resource spends 3 to 5 hours, and a contractor spends less than 2 hours repairing an elevator. These finding assist to timing the developed DES model for an order related to an elevator failure. These findings help to plan the developed DES model. This model simulates the workflow process from the time the order is registered in the system until it is executed.



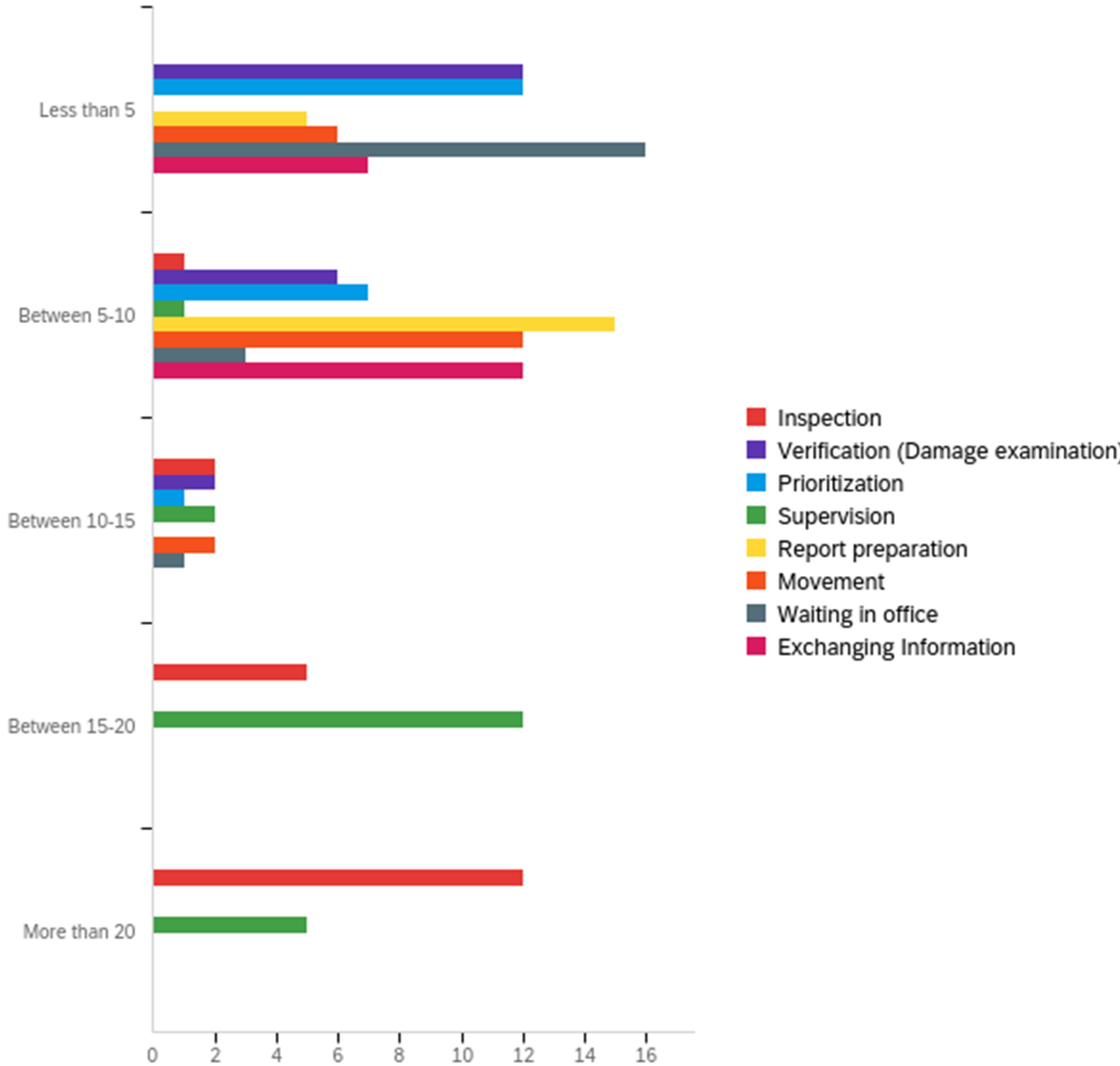
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Administration	1.00	3.00	1.30	0.64	0.41	20
2	Facility manager	1.00	2.00	1.95	0.22	0.05	20
3	Supervisor	2.00	3.00	2.15	0.36	0.13	20
4	Corrective resource	3.00	4.00	3.85	0.36	0.13	20

5	Maintenance resource	3.00	4.00	3.21	0.41	0.17	19
6	Outsourced to Contractor	1.00	2.00	1.25	0.43	0.19	20

#	Question	Less than 2 hours		Between 2- 3 hours		Between 3-5 hours		More than 5 hours		Total
1	**Administration**	80.00%	16	10.00%	2	10.00%	2	0.00%	0	20
2	**Facility manager**	5.00%	1	95.00%	19	0.00%	0	0.00%	0	20
3	**Supervisor**	0.00%	0	85.00%	17	15.00%	3	0.00%	0	20
4	**Corrective resource**	0.00%	0	0.00%	0	15.00%	3	85.00%	17	20
5	**Maintenance resource**	0.00%	0	0.00%	0	78.95%	15	21.05%	4	19
6	**Outsourced to Contractor**	75.00%	15	25.00%	5	0.00%	0	0.00%	0	20

Q29 - Indicate the total time (in hours) a supervisor spends on the following activities in a period of 40 hours-week?

According to the answers of the survey, 60% of participants indicated that a supervisor spends more than 20 hours working on inspection, between 15 to 20 hours on supervision, less than 5 hours on order verification and prioritization, and between 5 to 10 hours on movement. 75% of participants indicated that a supervisor spends between 5 to 10 hours on report generation, 80% of participants indicated that a supervisor spends less than 5 hours on waiting in office, and 63.16% stated a supervisor spends between 5 to 10 hours on for information exchange. These values are used to regulate the timing of a team coordinator agent (TCA) behaviors for 40 hours per week in the developed simulation model.



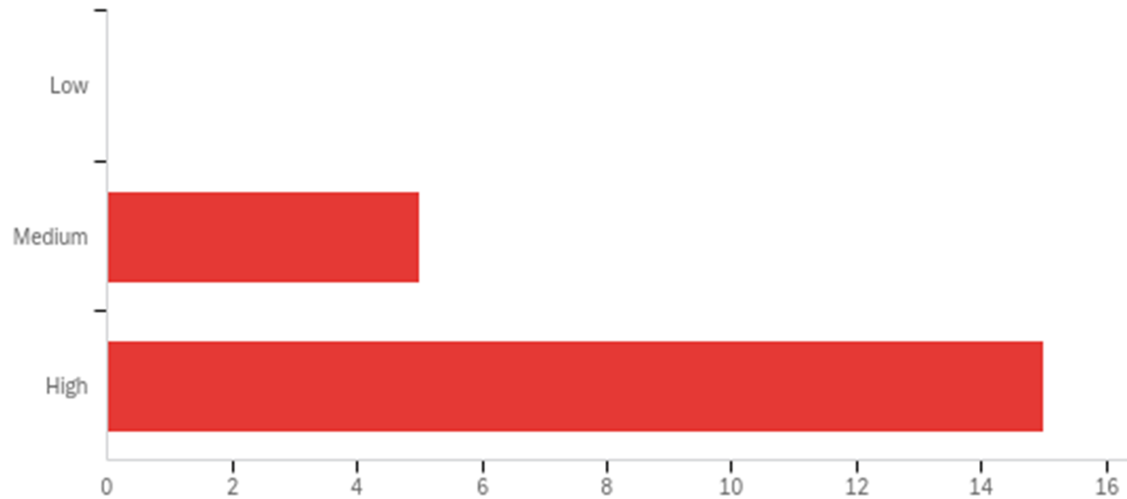
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Inspection	2.00	5.00	4.40	0.86	0.74	20
2	Verification (Damage examination)	1.00	3.00	1.50	0.67	0.45	20
3	Prioritization	1.00	3.00	1.45	0.59	0.35	20
4	Supervision	2.00	5.00	4.05	0.74	0.55	20

5	Report preparation	1.00	2.00	1.75	0.43	0.19	20
6	Movement	1.00	3.00	1.80	0.60	0.36	20
7	Waiting in office	1.00	3.00	1.25	0.54	0.29	20
8	Exchanging Information	1.00	2.00	1.63	0.48	0.23	19

#	**Question**	**Less than 5**		**Between 5-10**		**Between 10-15**	**n**	**Between 15-20**	**n**	**More than 20**	**n**	**Total**
1	**Inspection**	0.00%	0	5.00%	1	10.00%	2	25.00%	5	60.00 %	12	20
2	**Verification (Damage examination)**	60.00 %	12	30.00%	6	10.00%	2	0.00%	0	0.00%	0	20
3	**Prioritization**	60.00 %	12	35.00%	7	5.00%	1	0.00%	0	0.00%	0	20
4	**Supervision**	0.00%	0	5.00%	1	10.00%	2	60.00%	12	25.00 %	5	20
5	**Report preparation**	25.00 %	5	75.00%	15	0.00%	0	0.00%	0	0.00%	0	20
6	**Movement**	30.00 %	6	60.00%	12	10.00%	2	0.00%	0	0.00%	0	20
7	**Waiting in office**	80.00 %	16	15.00%	3	5.00%	1	0.00%	0	0.00%	0	20
8	**Exchanging Information**	36.84 %	7	63.16%	12	0.00%	0	0.00%	0	0.00%	0	19

Q30 - Please indicate the Risk Priority (likelihood of occurrence, likelihood of detection, and severity of impact) for elevator failure.

According to the answers of the survey, 75% of participants indicated that the risk priority for elevators is high, while 25% stated that this priority is medium for elevators.



#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Risk Priority for elevator failure	2.00	3.00	2.75	0.43	0.19	20

#	Answer	%	Count
1	**Low**	0.00%	0
2	**Medium**	25.00%	5
3	**High**	75.00%	15
	Total	100%	20

Appendix F: Sample Data Collected from FM of Concordia University

The file contains data in the form of excel sheet.

✓ Work number	✓ Problem code	✓ Status date	✓ Labor Hours
✓ Location	✓ Failure code	✓ Report date	✓ Billable
✓ Work type	✓ Description	✓ Status	

LOCATION	WORKTYPE	PROBLEMCODE	FAILURECODE	LEADCRAFT	DESCRIPTION	TLABH	STATUSDATE	REPORTDATE	STATUS	BILLABLE
S-MB				SDIST	Furniture left in the MB 7th floor Hallways	0.00	Jan 3, 2013 2:03:23 PM	Jan 2, 2013 4:16:29 PM	CAN	0
S-GN	COR	CLIENT/RQ	FURN/FIXT	SACRP	WINDOWS NEED TO BE SEALED: M-409, M-41	0.00	Jan 9, 2013 7:14:18 AM	Jan 4, 2013 1:14:49 PM	CAN	0
S-GN	COR	CLIENT/RQ	FURN/FIXT	SDIST	AS PER CALLER SHE TEACHES AT GN-M-100 O	0.00	Jan 9, 2013 1:19:26 PM	Jan 7, 2013 2:15:32 PM	CAN	0
L-VE	COR	BLOCKAGE	BLDG/EQUI	LMPLUM	see long description	0.00	Jan 10, 2013 9:41:33 AM	Jan 10, 2013 5:43:56 AM	CAN	0
S-GN	REQ	CLIENT/RQ	FURN/FIXT	SALOCK	CHANGE CORE	0.00	Jan 10, 2013 10:49:16 AM	Jan 9, 2013 3:35:08 PM	CAN	1
L-VE	COR	BLOCKAGE	BLDG/EQUI	LMPLUM	PY-149: TOILETTE DES DAMES: TOILETTE BL	0.00	Jan 10, 2013 11:57:35 AM	Jan 10, 2013 10:55:54 AM	CAN	0
L-AD	COR	BLOCKAGE	BLDG/EQUI	LMPLUM	AD-103-14: TOILETTE BLOQUE.	0.00	Jan 10, 2013 12:00:14 PM	Jan 10, 2013 10:55:14 AM	CAN	0
S-FB				SACRP	barrier letting people out staying in up position	0.00	Jan 10, 2013 2:13:21 PM	Jan 5, 2013 11:36:39 PM	CAN	0
L-HA				LACRP	Door need to be pushed to close completely	0.00	Jan 14, 2013 11:39:30 AM	Jan 13, 2013 6:52:29 AM	CAN	0
S-MB	COR	CLIENT/RQ	FURN/FIXT	SACRP	ESTIMATE: Need a quote from carpentry. Rem	0.00	Jan 14, 2013 5:00:00 PM	Jan 14, 2013 8:37:11 AM	CAN	0
L-HB	COR	REPAIR	BLDG/EQUI	LACRP	unable to close window	2.50	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 5:09:51 AM	CLOSE	0
S-MB	COR	VANDALISM	BLDG/EQUI	SN	glue stuck to 2 of the Guy st main entrance dc	0.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 6:27:16 AM	CLOSE	0
L- RA	COR	REPAIR	BLDG/EQUI	LACRP	repair glass at rink	8.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 8:16:07 AM	CLOSE	0
L-SP	CAL		BLDG/EQUI	LEELEC	reprogrammer generatrice du campus loyola	4.15	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 8:27:21 AM	CLOSE	0
L-PE	COR		BLDG/EQUI	LEELEC	verifier control lumiere arena	3.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:02:56 AM	CLOSE	0
L-RF	COR		BLDG/EQUI	LEELEC	enlever monitoring du grenier	2.50	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:16:54 AM	CLOSE	0
S-H	COR	GARBAGE	CLEAN/GR	SN	GARBAGE NOT COLLECTED SINCE DECEMBER 1	0.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:19:27 AM	CLOSE	0
L-PS	COR		BLDG/EQUI	LEELEC	demonter control du composteur	4.50	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:24:27 AM	CLOSE	0
S-GN	COR	REPAIR	BLDG/EQUI	SMPLUM	24.12.12. - LA BARRIERE A L'ENTREE DU 1200	5.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:28:23 AM	CLOSE	1
S-LB	COR	LIGHT	FURN/FIXT	SELAMP	LB BURNT OUT LIGHTS AS EMAILED TO SEELE	3.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:31:27 AM	CLOSE	0
S-GM	COR	ELEV	ELEV/ESC	EXT	#3 - SOMEONE WAS TRAPPED AROUND 8:30	0.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:33:40 AM	CLOSE	0
S-GN	COR	TOO COLD	HVAC	SMPLUM	SECTOR 2F - TOO COLD	1.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:36:01 AM	CLOSE	1
S-FB	COR	TOO COLD	HVAC	EXT	FB-100: COLD AIR COMING OUT OF VENT AT I	0.00	Jan 15, 2013 12:00:00 AM	Jan 3, 2013 9:37:42 AM	CLOSE	0

Appendix G: Setting up the Optimization Experiment in Anylogic

The objective function is coded in Anylogic as follows.

Therefore, mean annual down-time of BCAs is calculated by following equation:

```
return (statsCoRepair.mean() * (RepairTime/CMANumber)) +
       (statsCoReplacement.mean() * (ReplaceTime/CMANumber)) +
       (statsCoMaintenanceCheckup.mean() * (MaintenanceTime/PMANumber)) +
       (statsCoFailed.mean() * (CheckingTime/TCANumber));
```

Where,

`statsCoRepair.mean()` is the mean number of BCAs in the "Repair" state,

`RepairTime` is the repair time,

`CMANumber` is the number of CMA,

`statsCoReplacement.mean()` is the mean number of BCAs in the "Replacement" state,

`ReplaceTime` is the replace time,

`CMANumber` is the number of CMA,

`statsCoMaintenanceCheckup.mean()` is the mean number of BCAs in the "MaintenanceCheckup" state,

`MaintenanceTime` is the maintenance time,

`PMANumber` is the number of PMA,

`statsCoFailed.mean()` is the mean number of BCAs in the "Failed" state,

`CheckingTime` is the checking time,

`TCANumber` is the number of TCA,

The solution space is limited to three decision variables including "`CMANumber`", "`PMANumber`", and "`TCANumber`". Fixed parameters are "`RepairTime`", "`ReplaceTime`", "`MaintenanceTime`", "`CheckingTime`".

Therefore, the objective function is coded as follows:

```
Expression: root.downTime(RepairTime,ReplaceTime,MaintenanceTime,CheckingTime
CMANumber,PMANumber,TCANumber)
```

The constraint condition is set as follows:

```
Expression: root.availabilityStatistics.mean()>= 0.8
```

Appendix H: Genetic Algorithm Optimization to Minimize the Mean Annual Down-Time of the Elevators (Published with MATLAB® R2014a)

Initially, NSGA-II was used to optimize resource utilization in this study, however, in the last step, OptQuest was used as the optimization engine because it is more compatible with Anylogic.

Problem Definition

```
global NFE;
NFE=0;

CostFunction=@(x)MinOne(x);   %CostFunction
nVar=50;                      % Number of Decision variables
VarSize=[1 nVar];             % Decision Variables Matrix Size
```

GA Parameters

```
MaxIt=350 ;                   % Maximum Number of Iterations

nPop=100;                     % Popoulation Size

pc=0.8;                       % Crossover Percentage
nc=2*round(pc*nPop/2)         % Number 0f Offsprings (Parents)

pm=0.3;                       % Mutation Percentage
nm=round(pm*nPop)             % Number of Mutatance

mu=0.05;                      % Mutation Rate

ANSWER=questdlg('Choose selection method:','Genetic Algorith',....
   'Roulette Wheel','Tournament','Random','Roulette Wheel');

UseRouletteWheelSelection=strcmp(ANSWER, 'Roulette Wheel');
UseTournamentSelection=strcmp(ANSWER,'Tournament');
UseRandomSelection=strcmp(ANSWER,'Random');
```

```
if UseRouletteWheelSelection
    beta=8;                       % Selection Pressure
end

if UseTournamentSelection
    TournamentSize=3;              % Tournament Size
end

pause(0.1);
```

```
nc = 16
nm = 6
```

Initialization

```
empty_individual.Position=[];
empty_individual.Cost=[];

pop= repmat(empty_individual,nPop,1);

for i=1:nPop

    % Initialize Position

    pop(i).Position=randi([0,1],VarSize);

    % Evaluation

    pop(i).Cost=CostFunction(pop(i).Position);

end

% Sort Population
```

```
Costs=[pop.Cost];

[Costs, SortOrder]= sort(Costs);

pop=pop(SortOrder);


% Store Best So1ution


BestSo1=pop(1);


%Array to Hold Best Cost Values


BestCost=zeros(MaxIt,1);


% Store Cost

WorstCost=pop(end).Cost;


%Array to Hold Number of Function Evaluations

nfe=zeros(MaxIt,1);
```

Main Loop

```
 for  it=1: MaxIt


    % Calculate Selection Probabilities

    P=exp(-beta*Costs/WorstCost);

    P=P/sum(P);


    % Crossover

    popc=repmat(empty_individual,nc/2,2);

    for k=1:nc/2


       % Select Parents Indices

      if UseRouletteWheelSelection

          i1=RouletteWheelSelection(P);

          i2=RouletteWheelSelection(P);
```

```
   end
   if UseTournamentSelection
       il=TournamentSelection(pop,TournamentSize);
       i2=TournamentSelection(pop,TournamentSize);
    end
    if UseRandomSelection
       i1=randi([1 nPop]);
       i2=randi([1 nPop]);
    end

    % Select Parents
     p1=pop(i1);
     p2=pop(i2);

    % Apply Crossover
    [popc(k,1).Position popc(k,2).Position]=Crossover(p1.Position,p2.Position);

    %Evaluate Offsprings
    popc(k,1).Cost=CostFunction(popc(k,1). Position);
    popc(k,2).Cost=CostFunction(popc(k,2). Position);

end
popc=popc(:);

% Mutation
popm=repmat(empty_individual,nm,1);
for k=1:nm

    %Select Parent
    i=randi([1 nPop]);
    p=pop(i);

    % Apply Mutation
    popm (k).Position=Mutate(p.Position,mu);
```

```
    % Evaluate Mutant
    popm(k).Cost=CostFunction(popm(k).Position);

end

% Create Merged Population
pop=[pop
     popc
     popm];

% Sort Population
Costs=[pop.Cost];
[Costs, SortOrder]=sort(Costs);
pop=pop(SortOrder);

% Update Worst Cost
WorstCost=max(WorstCost,pop(end).Cost);

% Truncation
pop=pop(1:nPop);



%Store Best Solution Ever Found
BestSol=pop(1);

%Store Best Cost Ever Found
BestCost(it)=BestSol.Cost;

% Store NFE
nfe(it)=NFE;

%Show Iteration Information
disp(['Iteration' num2str(it) ': NFE = ' num2str(nfe(it)) ' , Best Cost = ' num2str(BestCost(it))]);
```

```
    end
```

Results

```
    figure;
    plot(nfe,BestCost, 'LineWidth',2);
    xlabel('NFE');
    ylabel('Cost');
```

Objective Function

```
function z=MinOne(x)

 global NFE;
 if isempty(NFE)
     NFE=0;
 end

 NFE=NFE+1;

 z=sum(x);


end
```

Single Point Crossover Function

```
function[y1y2]=SinglePointCrossover(x1,x2)
 nVar=numel(x1);

 c=randi([1nVar-1]);

 y1=[x1(1:c)x2(c+1:end)];
```

```
 y2=[x2(1:c) x1(c+1:end)];


end
```

Double Point Crossover Function

```
function[y1y2]=DoublePointCrossover(x1,x2)


 nVar=numel(x1);


 cc=randsample(nVar-1,2);


 c1=min(cc);

 c2=max(cc);


 y1=[x1(1:c1)x2(c1+1:c2)x1(c2+1:end)];

 y2=[x2(1:c1)x1(c1+1:c2)x2(c2+1:end)];


end
```

Uniform Crossover Function

```
function[y1y2]=UniformCrossover(x1,x2)


 alpha=randi([01],size(x1));


 y1=alpha.*x1+(1-alpha).*x2;

 y2=alpha.*x2+(1-alpha).*x1;


end
```

Mutate Function

```
function y=Mutate(x,mu)


nVar=numel(x);

nmu=ceil(mu*nVar);

j=randsample(nVar,nmu);


y=x;

y(j)=1-x(j);


end
```

Roulette Wheel Selection

```
function i=RouletteWheelSelection(P)


  r=rand;

  c=cumsum(P);

  i=find(r<=c,1,'first');

end
```

Tournament Selection

```
Function i=TournamentSelection(pop,m)

    nPop=numel(pop);

    S=randsample(nPop,m);

    spop=pop(S);


    scosts=[spop.Cost];

    [~,j]=min(scosts);

    i=S(j);

end
```