CHAPTER III

RESERCH METHODOLOGY

This chapter presents the methodological framework employed to address the Operating Room (OR) resource planning and scheduling problem under uncertainty, in the context of post-pandemic surgical backlog recovery. The proposed approach comprises a two-phase decision-making model designed to (i) optimally allocate OR blocks across surgical specialties, and (ii) prioritize patients for surgery within each department using a multi-criteria decision-making (MCDM) framework.

3.1 Overview of the Proposed Framework

The methodology adopts a multi-stage, multi-objective optimization framework structured as shown in **Figure 3.1.1.**

1) Phase 1 Multi-Objective Optimization: OR Block Allocation Model

A mathematical programming model is formulated to allocate OR blocks to surgical specialties over a planning horizon. This model incorporates uncertainty in surgery durations and patient length of stay (LOS) and seeks to minimize both (a) disparities in backlog clearance time across departments and (b) total operational costs associated with overtime, delays, and resource overflow.

2) Phase 2 Multi-Criteria Decision Making: Patient Prioritization Model

Within each specialty, an MCDM technique is applied to ranked patients based on a set of clinical and operational criteria (e.g., urgency, waiting time, resource utilization). This phase aims to ensure equitable and effective use of the assigned OR time blocks, aligning prioritization with both patient need and hospital constraints.
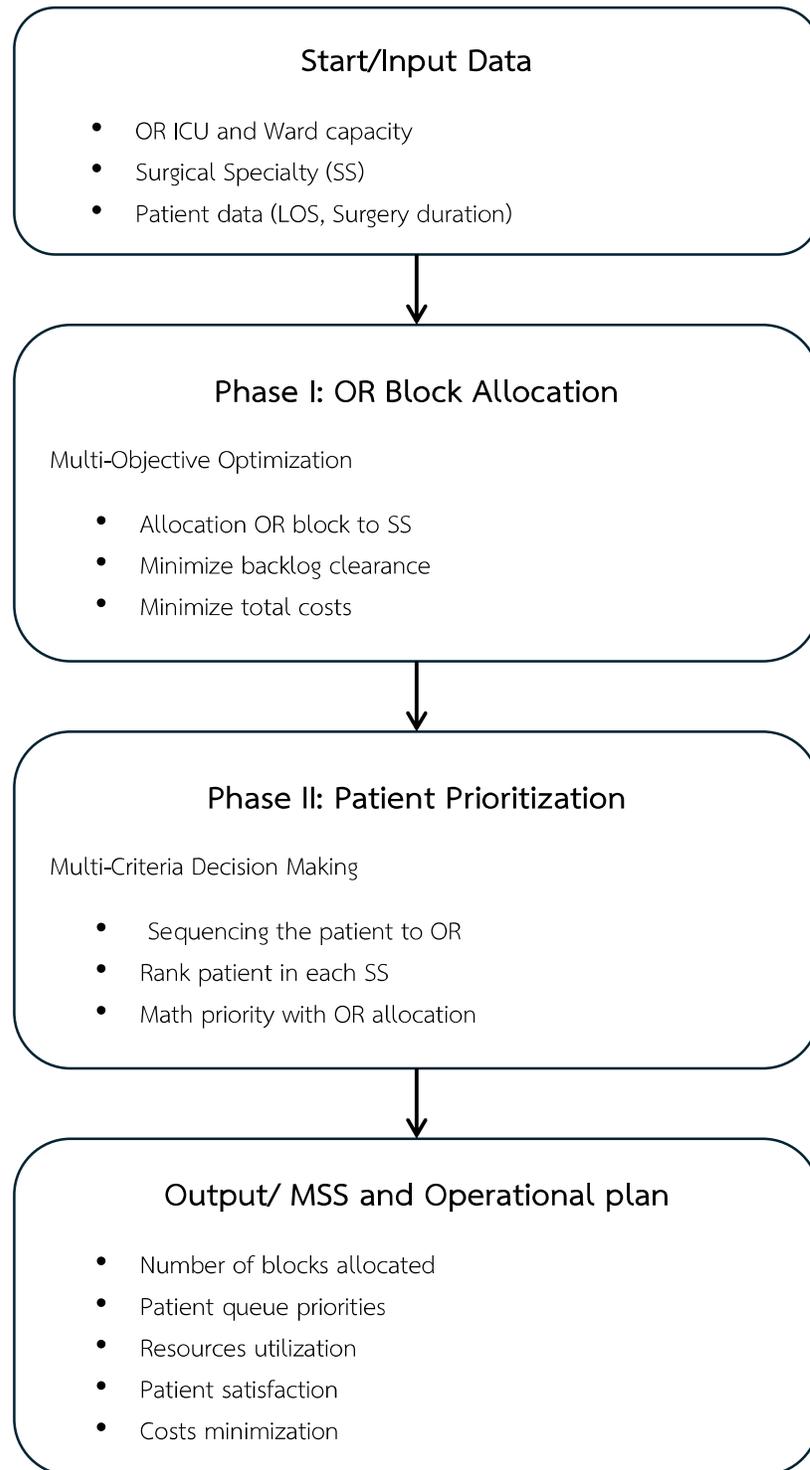
Start/Input Data

- OR ICU and Ward capacity
- Surgical Specialty (SS)
- Patient data (LOS, Surgery duration)

Phase I: OR Block Allocation

Multi-Objective Optimization

- Allocation OR block to SS
- Minimize backlog clearance
- Minimize total costs

Phase II: Patient Prioritization

Multi-Criteria Decision Making

- Sequencing the patient to OR
- Rank patient in each SS
- Math priority with OR allocation

Output/ MSS and Operational plan

- Number of blocks allocated
- Patient queue priorities
- Resources utilization
- Patient satisfaction
- Costs minimization

Figure 3.1.1. Proposed Framework

3.2 General Patient Flow and Resource Consideration

The general flow of patients is depicted in **Figure 3.2.1**, which illustrates the journey of a surgical patient from hospital arrival to discharge. Upon arrival, patients are first classified as elective or non-elective. Depending on their clinical condition, they may require pre-operative stays before surgery. After surgery, patients may either be treated as outpatients or require further hospitalization. Postoperative care could involve admission to the ICU or direct transfer to a surgical ward, based on the severity and type of surgery performed. All admitted patients are eventually discharged upon recovery.
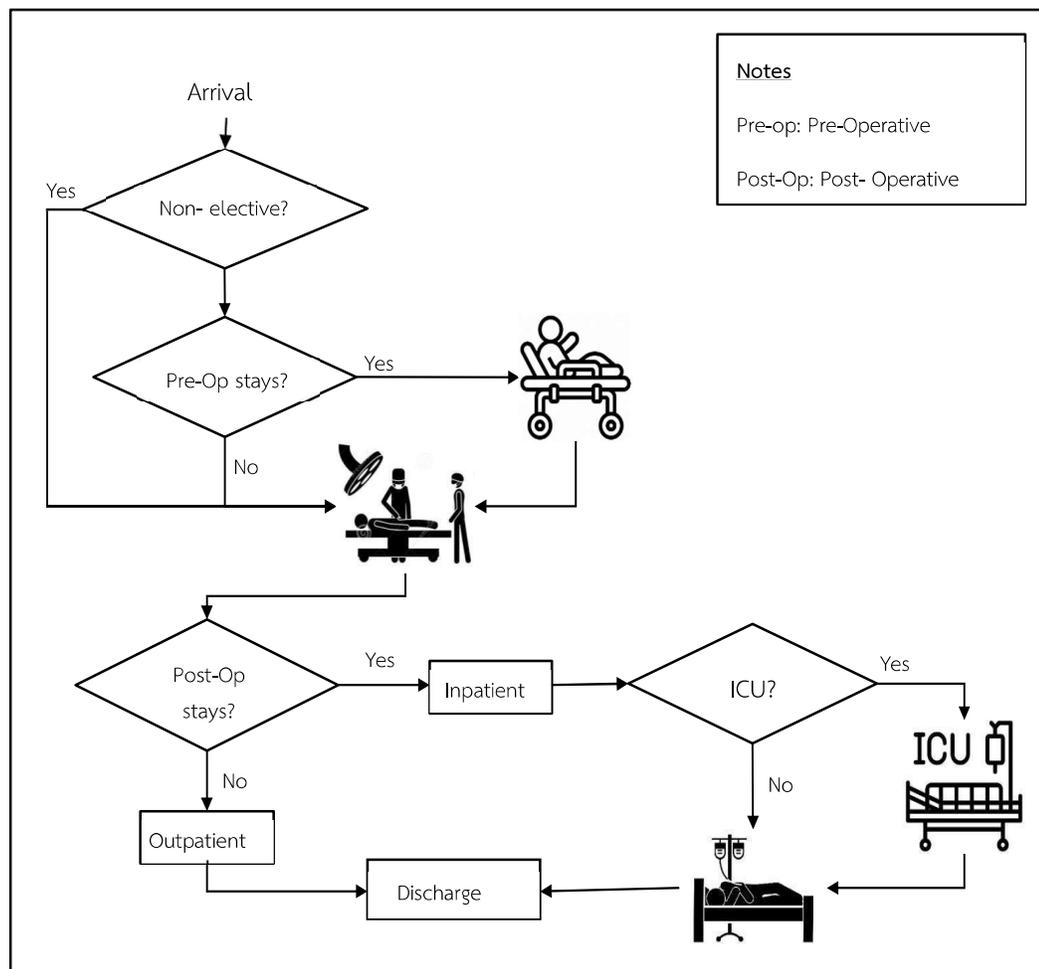

Figure 3.2.1 General Patient Flow Decision

To simplify the patient flow, this section presents the surgical patient flow and the resource structure that is used in this study. The primary goal is to allocate OR blocks efficiently across different surgical specialties (SS), considering variability in surgical duration and postoperative care needs, such as length of stay (LOS) in the ICU and surgical wards. These resources represent the primary capacity constraints in the elective surgery system. As illustrated in **Figure 3.2.2**, surgical patients utilize a sequence of resources beginning with the pre-operation stay then OR, followed by a recovery phase in either the ICU or surgical ward, depending on their clinical needs. The model assumes the availability of essential human resources, including surgical teams (surgeons, anesthetists, and support staff).

The associated costs for staff are incorporated into the fixed and variable cost components of OR block operation, including overtime utilization when applicable. Other healthcare resources—such as nursing hours, ancillary staff, laboratories, and diagnostic services—are assumed to be non-limiting and are thus excluded as constraints in the model. This assumption is consistent with similar studies and helps focus the optimization on the most critical and capacity-constrained elements of the surgical delivery system. By incorporating uncertainty in patient-level demand and focusing on resource bottlenecks, the proposed model aims to provide a robust planning tool that supports fair, efficient, and timely surgical service delivery in a post-pandemic recovery context.
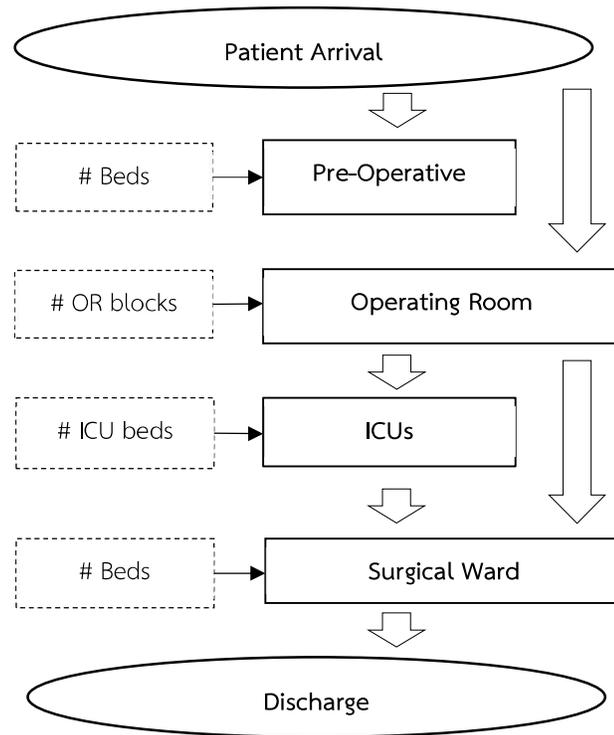
Figure 3.2.2 Patient flow and resources involved in the study

The planning model focuses on three critical and scarce resources within the surgical care pathway:

1) Operating Room (OR) Blocks – Defined as fixed time slots (typically 8 hours) allocated to surgeries.

2) ICU Beds – Required for patients needing intensive postoperative care.

3) Surgical Ward Beds – Used for routine preoperative and postoperative recovery following surgery or after ICU discharge.

3.3   Data collection

To support the development of the proposed two-phase decision-making framework, both primary and secondary data were collected from the study hospital. The data collection process was designed to ensure that all relevant clinical and operational information required for optimization modeling and patient prioritization

was captured comprehensively and accurately. Figure 3.3.1 illustrates the overall data collection process and procedure.

3.3.1 Primary Data

Primary data were obtained through direct engagement with key stakeholders within the hospital, including Surgeons and Clinical Staff: Interviews and consultation sessions were conducted to gather expert input on patient care pathways, clinical urgency criteria, and the practical challenges of operating room (OR) scheduling.

Hospital Administrators and Planners: Operational priorities and resource constraints were collected. Observation and Site Visits: The research team conducted direct observations within the OR, ICU, and surgical wards to understand workflow and validate the data provided. The primary data played a crucial role in defining the criteria for patient prioritization and resource allocation, which were later used in the Multi-Criteria Decision-Making (MCDM) model.

3.3.2 Secondary Data

Secondary data were extracted from the hospital's historical databases and administrative records as well as in literature review. These included:

1) **Surgery records**: Duration, frequency, and type of surgeries performed.
2) **Patient information**: Waiting list data, lengths of stay in ICU and surgical wards, and departmental backlog levels.
3) **Resource utilization reports**: OR block usage, ICU and ward bed occupancy rates.
4) **Cost data**: Including fixed and variable costs associated with OR operations.

This data was essential for statistical analysis and the construction of the OR Block Allocation Model, where variability and uncertainty (e.g., in surgery duration or LOS) were accounted for using probabilistic modeling.
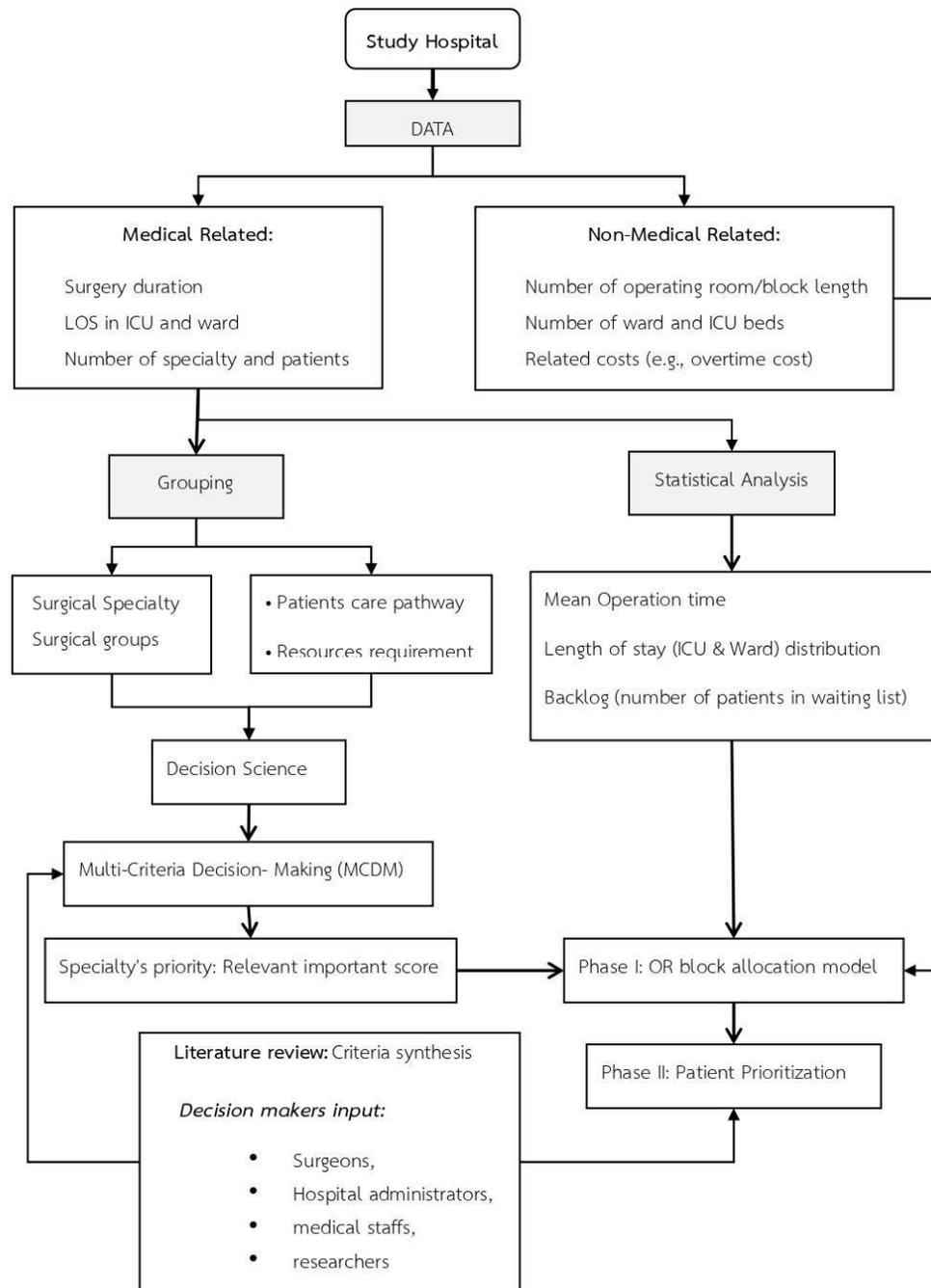
Figure 3.3.1 Data Collection Process and Procedure

3.4   Model Development

To address the OR block allocation and scheduling problem, a two-phase mathematical model is proposed:

4.1   Phase 1 Multi-Objective Optimization: OR Block Allocation Model

3.4.1.1 Research Procedure

This section describes the overall processes of the proposed mathematical model for OR resources allocation as shown in **Figure. 3.4.1.** First, parameters and decision variables are described. Then, the multi-objective optimization model is formulated and explained. We provide an overview of the mathematical model including the objective functions, constraints, and datasets from a large hospital for verifying the model and validating the model with sensitivity analysis.
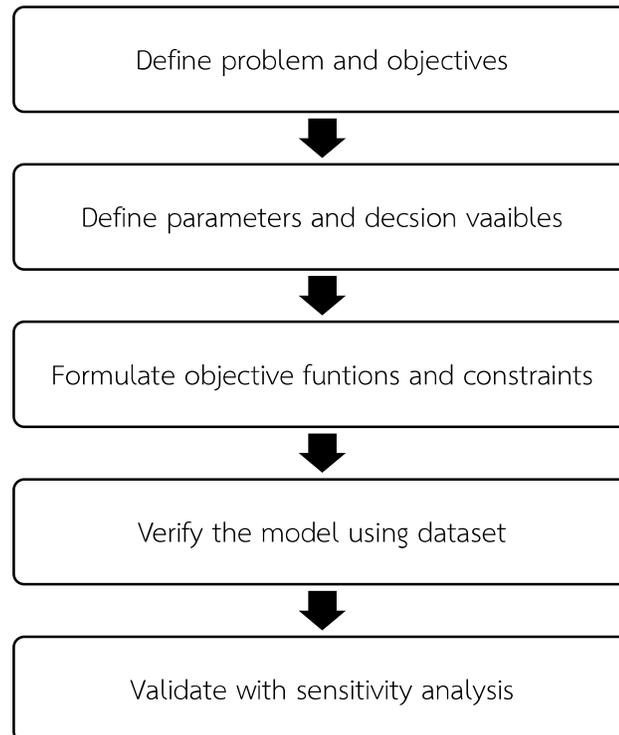
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│     Validate with sensitivity analysis     │
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Figure 3.4.1 Overall process

The research procedure in research is categorized into 10 steps as follows:

1) Study the process and patient flow of elective surgery from literatures and collect specialty related data and non-specialty related data from studies hospital and synthesis from literatures.

2) Define parameters/ constraints relating OR block allocation problem.

3) Calculate the patient flow into downstream unit (as an input parameter of the block allocation model.

4) Develop the mathematical model of operating room block allocation problem.

5) Verify and validate the model using mathematical methods.

6) A case study of a public hospital: use the data from the hospital studied to test the model.

7) Determine the optimal block allocated to each specialty that results in such a way that the total cost is minimized and the waiting time of each patient of each specialty is optimal.

8) Develop a Master Surgery Scheduling based on allocated blocks

9) Scenario analysis as well as benefit cost analysis of the trade-off between time (waiting list clearance time) and money (total incur costs) for informing the hospital administrators at what cost the hospital should pay to increase patient satisfaction by reducing waiting time.

10) Sensitive analysis: to study how changes in specialty priority (relevant score) input parameters of a model affect the output (total cost incur and time to clear the waiting list).

We address the problem of multiple resource allocation of ORs and propose a surgery scheduling scheme for OR units. To solve this problem, a multi-phase and integrated multi-objective linear programming model is proposed. The first step is an OR resource allocation model. The goal is to optimize the allocation of OR resources to each SS during the planning period. The proposed model is a resource allocation model, which mainly focuses on the allocation of ORs block for each surgical specialty (SS). Based on the results of the first phase, the second step is the master surgical schedule (MSS) model. Hence, the main problem to be solved in our study is the

allocation of number of ORs block (1 block equal to 8 hours) to different surgical specialties (SSs) belonging to the same hospital system and then developing a master surgery schedule (MSS) over a planning horizontal based on number of allocated blocks of each department.

This work proposes a mixed integer nonlinear programming model (ILP) considering integrating case-mix planning (CMP) and the master surgical scheduling (MSS) problems. The problem deals with the planning of the number of operating rooms block to be assigned to surgical specialties.

3.4.1.2 Parameters and decision variables
Notations

The following notations are used to develop the mixed integer non-linear programming (MINLP) model for the OR resources allocation problem, aiming to minimize the patient waiting time and the total cost incurred associated with OR blocks allocation.

Indices:	
T	Weekly planning horizon
t	Index of days, t=1.... T
s	Index of number of surgical departments, s=1.... S
r	Set of resources including operating room (*or*), intensive care unit (*icu*), medium care unit (*mcu*), and nursing hours (*nh*)
Parameters	
O_s	The average operation duration of surgical specialty *s*
P_s	Relative important weight of specialty *s*
μ_s	Average number of patients per OR block for specialty *s*
$l_{s,up}$	Average LOS of surgical specialty *s* patients in *MCU* before surgery
$l_{s,down}$	Average LOS of surgical specialty *s* patients in *MCU* after surgery and *ICU*
$l_{s,icu}$	Average LOS of surgical specialty *s* patients in *ICU* after surgery

nw_s	Average nursing workload (in hours) require for specialty s patients in _ICU_
$C_{r,t}$	Available capacity of resource r on day t, $r\hat{I}R=\{or,icu,mcu,nh\}$
φ_r	Maximum overtime of resources allowed for resources r over T and T
$U_{r,T}$	Target utilization of resources $r\hat{I}R=\{or\}$ in planning horizon T and T
Dem_s	Weekly demand of surgical specialty s
WL_s	Total patients waited in each surgical department s
Req_T^{max}	Maximum requirement number of OR blocks of specialty over T
Req_T^{min}	Minimum requirement number of OR blocks of specialty over T
$WCost_s$	Cost of waiting to surgery for patients from specialty s
$OCost_r$	Cost of over capacity of resources r
w_W	Relative weight of patient waiting time
w_O	Relative weight of overtime cost
Decision variables:	
x_{sT}	Number of OR blocks assign to surgical departments s in planning horizon T
$T_{WL,s}$	Number of weeks required to clear patients waiting list of surgical s
∂_{TC}	Average number of weeks required to clear patients' waiting list in hospital
$o_{r,T}$	Overcapacity of resources r needed over T and T+2
$U_{r,T}$	Utilizations of resource r over T and T+2

3.4.1.3 Mathematical model

The proposed model consists of two objectives, namely, minimizing patient waiting times (1) and minimizing total incurred costs (2). In (1), involves calculating the cumulative waiting cost for all surgical departments that is needed to minimize. This is achieved by multiplying the weekly waiting cost for each surgical discipline and the number of patients on each surgical department's waiting list by the decision variable, number of weeks required to clear the patient waiting list.

3.4.1.4 Objective Functions

The model solution aims to minimize the average patient waiting time of each surgical department denoted as $T_{WL,s}$.

$$Minimize\ Z_w = \sum_{s}^{S} \sum_{t=1}^{T} \left(T_{WL,s} \cdot WCost_s \cdot WL_s \right) \tag{1}$$

$$Minimize\ Z_O = \sum_{r}^{R} \sum_{t=1}^{T} \left(o_{r,T} \cdot P_s \cdot OCost_r \cdot \partial_{TC} \right) \tag{2}$$

In (1) represents the objective function aimed at minimizing the total cost associated with patient waiting times on the surgical waiting list. In (2), the formulation comprises four cost components which are costs associated with the overcapacity of OR, ICU, MCU, and nursing workload. It computes the overall overcapacity cost of all resources by multiplying unit values of overcapacity for these resources by the unit cost and then multiplying by the average waiting list clearance time.

These two distinct formulas then can be converted into a unified objective function, as shown in (3) below. The objective function (3) is referred to as the "total incurred cost".

$$MIN\ Z = \quad w_w \cdot Z_w + w_o \cdot Z_o \tag{3}$$

The weighing of each objective function $w_w\ and\ w_o$ can be interpreted as a reflection of the hospital's preferences toward the performance indicators. In general, different hospitals may have different priorities in weighing different performance indicators due to various factors. This model assumed that the weight of the objectives equally the same $w_w = w_o = 1$.

3.4.1.5 Constraints

This section outlines constraints considered in our model.

$$\sum_{t=1}^{T-2} x_{sT} \leq \sum_{t=1}^{T-2} C_{r,t} \qquad \forall r \in \{or\}, \qquad \forall s \in S \qquad\qquad (4)$$

$$\sum_{s=1}^{S} \left(x_{sT} \cdot \mu_s \cdot l_{s,icu}\right) \leq \sum_{t=1}^{T} C_{r,t} \quad \forall r \in \{icu\}, \qquad \forall t \in T \qquad\qquad (5)$$

$$\sum_{s=1}^{S} \left\{x_{sT} \cdot \mu_s \cdot \left(l_{s,up} + l_{s,down}\right)\right\} \leq \sum_{t=1}^{T} C_{r,t} \quad \forall r \in \{mcu\}, \qquad \forall t \in T \qquad\qquad (6)$$

$$\sum_{s=1}^{S} \left(x_{sT} \cdot \mu_s \cdot nw_s\right) \leq \sum_{t=1}^{T} C_{r,t} \quad \forall r \in \{nh\}, \quad \forall t \in T \qquad\qquad (7)$$

Constraint (4) ensures that the number of allocated OR blocks do not exceed available OR blocks in one-week planning horizon. T-2 as OR operated 5 days a week.

Constraint (5) ensures that required ICU time for all patients in planning horizons does not exceed available ICU.

Constraint (6) determines the total amount of time needed for both preoperative and postoperative stays. This constraint ensures that the number of patients admitted to the MCU following surgery and prior to surgery does not exceed available MCU beds in one-week planning horizon.

Constraint (7) is crucial for imposing constraints on the maximum allowable overtime for all resources over one-week of planning horizon. They ensure that the variables denoting overcapacity for OR blocks, ICU time, MCU and nursing time do not exceed the maximum permissible threshold of resource facilities.

It is calculated as the total supply capacity for each resource multiplied by the corresponding percentage allowance which is derived from the hospital perspective.

$$o_{r,t} \leq \varphi_r \cdot \sum_{t=1}^{T-2} C_{r,t} \quad \forall r \in \{ or \}, \qquad \forall t \in T \qquad (8)$$

$$o_{r,t} \leq \varphi_r \cdot \sum_{t=1}^{T-2} C_{r,t} \quad \forall r \in \{ icu, mcu, nh \}, \qquad \forall t \in T - 2 \qquad (9)$$

To optimize the utilization of resources, including OR, ICU, MCU, and ICU nursing workload, it is essential to establish constraints that ensure that these resources are used effectively. **Constraint (10)** is formulated to set the minimum requirements for the utilization of these resources.

$$U_{r,T} \geq Req_{r,T}^{uti} \quad \forall r \in \{ or, icu, mcu, nh \} \qquad (10)$$

Constraints (11) and **(12)** play a significant role in defining boundaries for the allocation of OR blocks to each specialty over the planning period. These constraints determine both the lower and upper limits for the number of OR blocks that should be allocated to each department. This perspective reflects the minimum and maximum service level provided to patients from less profitable surgical departments.

$$\sum_{s}^{S} \sum_{t=1}^{T-2} x_{sT} \geq Req_{s,T}^{min} \qquad \forall r \qquad (11)$$

$$\sum_{s}^{S} \sum_{t=1}^{T-2} x_{sT} \leq Req_{s,T}^{min} \qquad \forall r \in \{or\} \qquad (12)$$

The **constraint (13)** guarantees that the allocation of OR blocks must be adequate to clear the weekly demand of each specialty over the planning period.

$$\sum_{t=1}^{T-2} x_{sT} \cdot \mu_s \geq Dem_s \qquad \forall s \in S \qquad (13)$$

The **constraint (14)** ensures that the total number of blocks assigned to all specialties collectively must be sufficient to handle total patient throughput weekly.

In other words, the resource allocation should be capable of accommodating the combined needs of all patients across various surgical departments within a given week.

$$\sum_{t}^{T}\sum_{s}^{S}(x_{sT} \cdot \mu_s \cdot \partial_{TC}) \geq \sum_{s}^{S} Wl_s \tag{14}$$

Finally, **constraint (15)** restricts all decision variables to be positive integer values and **constraint (16)** is the non-negativity of resources utilization, overcapacity of resources r, number of weeks required to clear patients waiting list of surgical s, average number of weeks required to clear patients waiting list in hospital.

$$x_{sT} \in \mathbb{N} \quad , \quad s \in S, \qquad t = 1,2,\dots,T+2 \tag{15}$$

$$U_{r,T} \geq 0, \quad o_{r,T} \geq 0, \qquad T_{WL,s} \geq 0, \quad \partial_{TC} \geq 0, \quad r \in R, t = 1\dots.T+2 \tag{16}$$

3.4.2 Phase 2: Patient Prioritization via MCDM

This study employs a systematic approach to evaluating the potential and sustainability of HWT in Nakhon Ratchasima Province. The methodology consists of six key stages as shown in **Figure 3.4.3**.
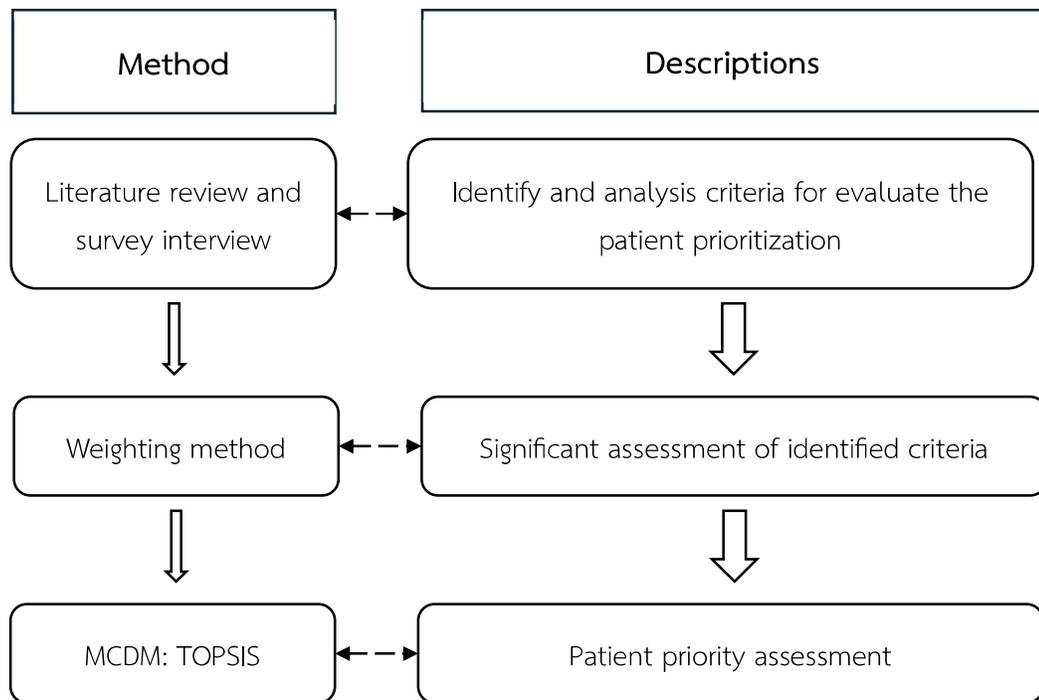

Figure 3.4.3 Research framework.

1. Literature Review and Expert Interviews/Assessment: A comprehensive literature review and expert interviews are conducted to identify and analyze the critical criteria for evaluation and assess the patient priority
2. Weighting Method for identified criteria: A weighting method is applied to prioritize the criteria and sub-criteria.
3. Multi-Criteria Decision Making (MCDM): TOPSIS is used as an MCDM approach to evaluate the patient priority. This method ranks the patient in each department based on their characteristic respected to identified criteria and sub-criteria

3.4.2.1 Criteria Identification

Literature Review and Expert Interviews/Assessment: A comprehensive literature review and expert interviews are conducted to identify and analyze the critical criteria for evaluation and assess the patient priority

3.4.2.2 *Criteria scoring*

Scoring function was applied to estimate each weight value of the sub-criteria. Experts were allowed to assess each value based on preference score e from 0 (extremely unimportant) to 10 (extremely important). The indices and parameters is shown below:

Indices	
i	index of criteria or sub-criteria, where i =1, 2,...,n
j	Index of alternatives, where j =1,2,...,m
e	Index of expert or decision-maker e=1,2,...,E
Parameters	
$x_{i,j}$	Performance score of alternative j with respect to criterion i
$\mu_{i,e}$	Preference score given by expert e to criterion i ranging from 0 (extremely unimportant) to 10 (extremely important)
w_i	Normalized weight of criterion i, calculated based on expert scores
W	Sum of all preference scores for all criteria across experts
$n_{i,j}$	Normalized value of $x_{i,j}$ in the decision matrix
$v_{i,j}$	Weighted normalized value of $x_{i,j}$
v_{ij}^-	Negative ideal solution vector, composed of the worst values for each criterion
v_{ij}^+	Positive ideal solution vector, composed of the best values for each criterion
d_j^+	Separation (Euclidean distance) of alternative j from the positive ideal solution
d_j^-	Separation of alternative j from the negative ideal solution
R_j	Relative closeness of alternative j to the ideal solution

Afterwards, the corresponding weight for each criterion i = {1, 2..., n}, Wi is given by:

$$w_i = \frac{1}{W} \sum_{e=1}^{10} \mu_{i,e} \tag{17}$$

$$Where \ W = \sum_{i=1}^{n} \sum_{e=1}^{10} \mu_{i,e} \tag{18}$$

3.4.2.3 TOPSIS

(1) Calculate the normalized decision matrix. The normalized value n_{ij} is calculated as

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^{2}}} \quad ; \ j = 1,2,\dots..m \ ; i = 1,2,\dots.n \tag{19}$$

(2) Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as:

$$v_{ij} = w_i \times n_{ij} \qquad ; \ j = 1,2,\dots..m \ ; i = 1,2,\dots.n \tag{20}$$

Where w_i is the weight of the ith attribute or creation and criterion, and $\sum_{i=1}^{n} w_i = 1$

(3) Determine the positive ideal and negative ideal solution.

$$A^{+} = \{v_1^{+}, v_1^{+}, \dots\dots, v_n^{+}\} = \left\{ \left(max_j \ v_{ij} | i \in I \right), \left(min_j \ v_{ij} | i \in J \right) \right\} \tag{21}$$

$$A^{-} = \{v_1^{-}, v_1^{-}, \dots\dots, v_n^{-}\} = \left\{ \left(min_j \ v_{ij} | i \in I \right), \left(max_j \ v_{ij} | i \in J \right) \right\} \tag{22}$$

Where I is associated with benefit criteria, and J is associated with cost criteria.

(4) Calculate the separation measures using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is calculated as:

$$d_j^+ = \sqrt{\sum_{i=1}^{n}\left(v_{ij} - v_{ij}^+\right)^2} \qquad ; j = 1,2, \ldots \ldots \ldots \ldots \ldots m. \tag{23}$$

Similarly, the separation from the negative ideal solution is given as

$$d_j^- = \sqrt{\sum_{i=1}^{n}\left(v_{ij} - v_{ij}^-\right)^2} \qquad ; \; j = 1,2, \ldots \ldots \ldots \ldots \ldots m. \tag{24}$$

(5) Calculate the relative closeness to the ideal solution. The relative closeness of the alternative:

$$R_j = \frac{d_j^-}{d_j^+ + d_j^-} \qquad ; i = 1,2, \ldots \ldots , m. \tag{25}$$

Since $d_j^- \geq 0 \; and \; d_j^+ \; \geq 0, \; then, \; clearly \; R \in [0,1].$

(6) Rank the preference order

3.5   Numerical case study: overview of hospital dataset

The datasets for numerical analysis were collected from a large hospital with more than 5000 surgical interventions per year. There are 8 different surgical groups: ear, nose, and throat (ENT), obstetrics and gynecology (OBG), orthopedic surgeries (ORT), neurosurgery (NEU), general surgeries (GEN), vascular surgeries (VAS), cardiac surgeries (CAR), and urology surgeries (URO) in the hospital. There are 8 operating rooms, one of these is dedicated to emergency patients. As detailed in Table 3.1.

The hospital operates these OR on 8-hour surgical blocks during regular time from Monday to Friday. There are 20 ICU rooms and 35 MCU beds, which operate continuously, 24 hours a day, seven days a week. Additionally, there are 60 nurses available in the ICU. Mean surgery duration, mean LOS in the ICU and MCU (pre and postoperative stay), mean ICU nursing hours needed are adopted from historical data and statistics provided in literature.

Resources required by each surgical patient and overall resources availability are measured in hours. We assume that any patient can access any available ICU or MCU beds and MCU beds are used for both preoperative and postoperative in planning horizon.

Table 3.1 Resource requirement for each specialty

Specialty	Surgery Duration (hrs)	ICU-LOS (hrs)	MCU-LOS (hrs)		ICU nursing care (hrs)
			Pre-Op	Post-Op	
ENT	1.23	3	0	12	3
OBG	1.43	10	12	12	10
URO	1.06	7	12	12	7
GEN	1.55	6	0	24	6
VAS	2	48	24	72	48
OTH	1.78	36	12	48	36
NEU	2.67	72	24	48	72
CAR	4	72	24	72	72

Before the pandemic, OR blocks were allocated based on the number of patients in each surgical department and the limited availability of downstream facilities. As detailed in Table 3.2, the number of patients in each surgical department was assessed and the number of OR blocks assigned. Based on the current setting, over a week of planning horizontal it resulted in an average of 90% of resources being used and the average waiting time of the patient in each department is 41.32 weeks.

Table 3.2 Current OR block assignment

Specialty	No. Blocks assigned	Number of patients in waiting list	Expected Waiting time (weeks)
ENT	5	1092	36.4
OBG	3	468	31.2
URO	3	416	34.67
GEN	5	1144	31.77
VAS	3	416	52
OTH	5	1196	42.71
NEU	3	260	43.33
CAR	1	104	52