Operating room workforce planning and scheduling: A multi-agent simulation for decision support

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For goddess of knowledge, Saraswati
For parents Dilip and Snehal
For wife Abha
For sons Mayank and Aditya

Abstract

Hospitals, especially in the developed world, currently face new challenges such as the rising cost of healthcare services, unsustainable healthcare system, ever-growing scarcity of skilled human resources for medical services, and the ongoing COVID-19 pandemic. A business process transformation through digitalization and value-orientation is vital to address them. Consequently, there has been renewed interest in implementing computer simulations for hospital decision support with focus on core as well as enabling business processes. The cornerstone of this work is the contextual and conceptual development of a multi-agent computer simulation model—based on enterprise architecture frameworks—for operating room workforce planning and scheduling. The model can aid operating room schedulers and managers making fact-based decisions for real-world underlying business processes and real-time information concerning resources. A Lerncockpit-integrated prototype, analogous to an aircraft, with classical and value-based key performance indicators is realised. It helps the scheduler arrive at better decisions as compared with conventional methods.

The simulation results demonstrate that the performance indicators, namely productivity, quality, cost, and customer satisfaction, are interrelated and are directly or inversely proportional to the input parameters of the experiment, thus validating common knowledge. Additional analysis based on quantitative work sampling and qualitative interview data analysis can be valuable input for future computer simulations. Further, a benchmarking study based on the data collected from both German and American hospitals provides insight into the operating rooms workforce planning and scheduling business process. The benchmark survey shows that operating room staff working at an American hospital are more satisfied than their German counterparts. Future simulation models will require data on actual service cost and presence/absence of staff by using the internet of things (IoT) sensors so as to be more realistic. In general, the findings herein indicate that an enterprise architecture framework can be helpful while developing proof-of-concept applications based on new technology. A systematic application of the framework can foster standardization and rationalization of the future information technology landscape pertaining to hospitals.

Zusammenfassung

Die Krankenhäuser, vor allem in Industrieländern, stehen vor bereits bekannte als auch neuen Entwicklungen, wie z. B. den steigenden Kosten für die Gesundheitsversorgung, dem unhaltbaren Gesundheitssystem, dem zunehmenden Mangel an qualifiziertem Personal für medizinische Dienstleistungen und der anhaltenden COVID-19-Pandemie. Eine Transformation der Geschäftsprozesse durch die Digitalisierung und die Wertorientierung ist eine absolute Notwendigkeit, um diese Herausforderungen zu bewältigen. Dementsprechend besteht ein erneutes Interesse an der Implementierung von Computer-Simulationen zur Entscheidungsunterstützung in Krankenhäusern, wobei nicht nur die Kernprozesse, sondern auch die unterstützenden Prozesse im Mittelpunkt stehen. Der Schwerpunkt dieser Arbeit liegt auf der kontextbezogenen und konzeptionellen Entwicklung einer Multiagenten-Computer-Simulation für die Einsatzplanung im OP auf der Grundlage von Unternehmensarchitekturen. Eine solche Simulation kann einen OP-Planer und einen OP-Manager dabei unterstützen, sachbezogene Entscheidungen für die realen Geschäftsprozesse und die Echtzeitinformationen über die Ressourcen zu treffen. Ähnlich wie bei einem Flugzeug wird ein Prototyp mit einem integrierten Lerncockpit realisiert, das klassische und wertorientierte Kennzahlen aufweist und den Planer dabei unterstützt, bessere Entscheidungen zu treffen.

Die Simulationsergebnisse belegen, dass die Performance-Kennzahlen, wie z.B. Produktivität, Qualität, Kosten und Kundenzufriedenheit, zusammenhängen und sich direkt oder umgekehrt proportional zu den Input-Parametern des Experimentes verhalten, und sie bestätigen das allgemeine Fachwissen. Zusätzliche Bewertungen auf der Grundlage von quantitativen Multimomentaufnahmen und qualitativen Interview-Datenanalysen können einen wertvollen Beitrag für zukünftige Computer-Simulationen erbringen. Darüber hinaus bietet eine Benchmark-Studie, die auf den Daten von deutschen und amerikanischen Krankenhäusern aufbaut, einen Einblick in den Geschäftsprozess der Einsatzplanung und Disposition im OP. Die Benchmark-Studie zeigt, dass das OP-Personal in einem amerikanischen Krankenhaus insgesamt zufriedener ist als in einem deutschen Hospital. Ein zukünftiges Simulationsmodell benötigt Daten über die realen Betriebskosten sowie die An- und Abwesenheitszeiten des OP-Personals unter Nutzung des Internet of Things (IoT)-Sensors, um es realistischer zu gestalten.

Insgesamt zeigt diese Forschung, dass ein Rahmen für die Enterprise Architecture bei der Entwicklung von Proof-of-Concept-Anwendungen auf der Basis neuer Technologien hilfreich sein kann. Seine systematische Anwendung kann die Standardisierung und Rationalisierung der zukünftigen IT-Landschaft in den Krankenhäusern fördern.

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Contents

List of Symbols

Multi-Agent Simulation

A	Number of schedulers or agents
c_a	Cost of scheduler per unit time
c_{ext}	Cost of external workforce per unit time
D	A type of medical speciality/OR-type (e.g. orthopaedics)
d_{diff}	Difference between maximum and minimum d_{vac}
d_i	Amount of work done by an external with time index i
$d_{lost,q}$	Loss of presence from OR due to insufficient planning
DOY	Time instance in a simulation during an year
d_{vac}	Sum of additional vacation
d_{year}	Workdays per year
$e_{all,q}$	Aggregation of default and shortage events for an OR type
$e_{day,q}$	Counter for daily workforce-shortage events managed internally by staff type q
e_{def}	Counter for actual number of surgical operations defaulted
e_{ext}	Counter for shortage events managed by the OR coordinator
$e_{week,q}$	Counter for weekly workforce-shortage events managed internally by staff type q
f_x	Coefficient for satisfaction contribution of x
H	Number of ORs according to plan
H_{act}	Actual number of planned ORs
H_{init}	Initial number of planned ORs
i_{qual}	Input value for (medically skilled) qualified workforce scheduled
N	Number of days elapsed
OR_{act}	Actual number of planned surgical operations
OR_{hall}	Number of surgical operations per OR per day
OR_{init}	Initial number of feasible surgical operations
p_{ext}	Average number of externals in each OR-type
$p_{lost,q}$	Percentage of lost working time due to insufficient planning
$sat_{k,q}$	Contribution to (overall) satisfaction from category k of a medical profession q
s_q	Total number of workforce in a medical profession q (e.g. nursing)
$t_{a,i}$	Amount of time taken by scheduler a in a period with index i

$t_{day,i}$	Amount of time taken for daily planning in a period with index i
$t_{initial}$	Amount of time taken for initial (yearly and half-yearly) planning
t_{total}	Aggregation of time taken for planning by schedulers
$t_{week,i}$	Amount of time taken to do weekly planning in a period with index i

Survey

β	(Standard) Correlation coefficient
n	Number of responses or sample size
s	Standard deviation of the sample
R^2	Statistical measure of fit
t-value	Outcome of t-test

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List of Acronyms

ABMS Agent-Based Modelling & Simulation
ADM Architecture Development Method
AI Artificial Intelligence
ArchiMate Architecture Animate
BITA Business–IT Alignment
BELOUGA Benchmarking of Logistical Support and Service Processes in Healthcare and Industrial Applications
BPMN Business Process Model and Notation
BSC Balanced Scorecard
COVID-19 Coronavirus Disease 2019
CSSD Central Sterile Services Department
DSS Decision Support System
DES Discrete-Event Simulation
DSR Design Science Research
DT Digital Twin
EA Enterprise Architecture
E2E End-to-End
HRO High-Reliability Organization
HITL Human-In-The-Loop
ICT Information and Communication Technology
IoT Internet of Things
ICU Intensive Care Unit
IM Information Management
ISL Identification of Service Gaps
IT Information Technology
KPI Key Performance Indicator
MAS Multi-Agent System
MS Medical Supply
ORs Operating Rooms
OR-WPS Operating Room Workforce (Coverage) Planning and Scheduling
PM Performance Management
PoC Proof of Concept
PTL Patient Transport Logistics
SLR Systematic Literature Review
UI User Interface
UMHC University of Missouri Health Care
UMHS University of Missouri Health System
UML Unified Modelling Language

1 Introduction

Abstract: *This chapter presents an investigation of the open areas of research in healthcare business service, the subject matter and foreseen contributions of this work in the context of the business-related practical problems faced by healthcare service providers and the associated challenges. Elucidating the present research problem and their solution requires the introduction of a set of scientific concepts such as empirical evidence and computer simulation. The information from field studies are considered in concurrence with a literature review to formulate the research questions that this work sought to address. Further, the adopted research process and an overview of the thesis chapters are summarised.*

1.1 Motivation

Operating Rooms (ORs) are the health care service provider's highest cost and revenue centres. Substantial research has focused on avoiding their underutilization and managing its overutilization. Macario et al.[1] found that typical hospital services related to surgeries comprise more than 40% of hospital costs and revenues. They developed an even point system to evaluate OR efficiency based on staffing costs, start-time tardiness, case cancellation rate, delays, turnover times, and other aspects[2]. Studies have also been reported on making ORs efficient by using process management, such as that by Harders et al.[3] wherein the non-operative activities in the ORs were reduced by redesigning the process between operations. Although the core healthcare process with direct customer (patient) interaction is the most impor-

[1]Source: A. Macario et al. (1996), Where are the costs in perioperative care? Analysis of hospital costs and charges for inpatient surgical care [MAC+96]

[2]Source: Alex Macario (2006), Are your hospital operating rooms efficient? A scoring system with eight performance indicators [Mac06]

[3]Source: Maureen Harders et al. (2006), Improving operating room efficiency through process redesign [Har+06]

tant, an alternative strategy for process improvement should entail the investigation of the enabling processes by using an out-of-box approach. In addition to these specific healthcare service issues and their associated needs, at the national level, almost all developed countries, including Germany and the United States of America, are undergoing significant economic and social transformation. Specifically, Germany, which is transitionally a manufacturing hub and well known for its exports, aims to become climate neutral by 2045[4] and further develop value addition of the service sector including healthcare. Furthermore, the contribution of the services at 70.4% of the German national GDP[5] is significant, as shown in figure (1.1).

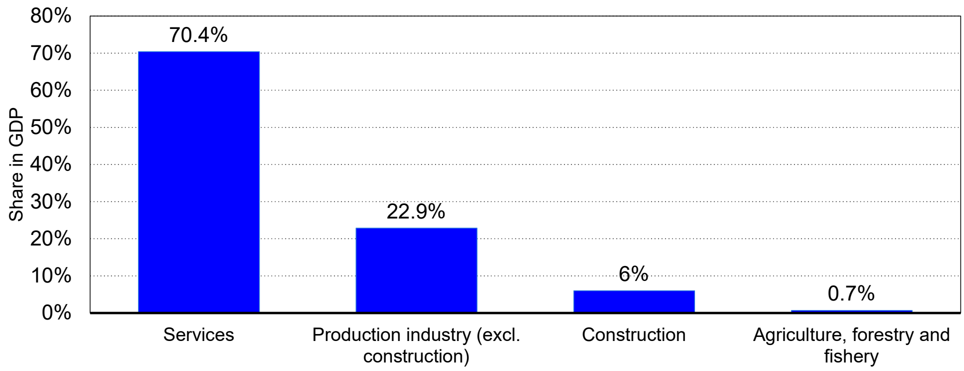


Figure 1.1: Germany's share of economic sectors in the gross domestic product (GDP) in 2020

Particularly in the healthcare service sector, the demographic changes pressure providers, such as hospitals, in Germany to reduce their total costs so as to be more profitable while keeping productivity, quality, and cost of its operations optimum. Compared to the other sectors such as retail, healthcare has been slow in embracing digitalisation/information technology in its value chain to reach its customers and in exploring innovative ideas for future adoption. However, the slow pace in adopting digitalisation has its reasons. A hospital should keep functioning well, and it must keep delivering its services even in crisis scenarios[6]. Specific sociopolitical, cultural, financial, and regulatory frameworks in Germany and the USA require the healthcare service sector to satisfy certain constraints on what a typical German and American

[4]Source: German national climate protection law (in German: Bundes-Klimaschutzgesetz)
[5]Source: Statistisches Bundesamt; ID 295519
[6]Note: A hospital should be a *high-reliability organization* (HRO).

hospital can do and what it cannot. On the basis of an analysis, Schlüchtermann[7] categorised the hospital management challenges into five broader categories, namely, (1) demographic developments, (2) changes in societal values, (3) legal frameworks, (4) increase in competition, and (5) medical and technological advancements. The 1^{st}, 2^{nd} and 3^{rd} challenges are environmental variables outside the control of healthcare service providers such as hospitals. They operate in a system wherein these aspects are a given. Focusing on them is, intentionally, out of the scope of this study. As regards the 4^{th} and 5^{th} challenges (i.e. increase in competition and medical and technical advancements, respectively), the findings from this this study can potentially contribute to value addition. Therefore, a limited analysis in the context of Operating Room Workforce (Coverage) Planning and Scheduling (OR-WPS) are presented in sections (1.1.1) and (1.1.2); this description helps provide the context for the following descriptions of the research.

(a) Increase in Competition (1.1.1)

(b) Medical and Technological Advancements (1.1.2)

1.1.1 Increase in Competition

Schlüchtermann[8] reported on the intensity of growing competition in healthcare services and its management, which is a topic of current practice and research. A few remarkable studies concerning the competition among hospitals in the healthcare service domain have been reported. In the late 80s, Noether[9] reported that the price competition among hospitals in the US, which was supposed to be non-existent, is not immune to standard competitive forces. From the perspective of the market, a patient must not visit a specific hospital only on the basis of geographical distance. Owing to the already improved logistics infrastructure in developed countries, patients can travel to a distant but reputed hospital with relative ease. This presents options at the disposal of the patients as well as a challenge for the hospitals to provide the best possible care with incurred costs under control and be attractive in the healthcare

[7] Source: Jörg Schlüchtermann (2013), Betriebswirtschaft und Management im Krankenhaus - Grundlagen und Praxis [Sch13]

[8] Source: Ibid

[9] Source: Monica Noether (1988), Competition among hospitals [Noe88]

service market. Eiriz et al.[10] and, subsequently, Pérez et al.[11] found that competitiveness dimensions are in terms of organizational, strategic behaviour and (operational) performance. In addition, Pérez et al.[12] investigated the role of Information and Communication Technology (ICT) as one of the factors in medical services to reduce costs and increase productivity and confirmed its positive contribution.

As the hospitals operate in a competitive environment, the operational performance can be focused on, with organizational dimension and strategic behaviour in the background. For instance, the focus can be on improving the business process, delivering products or services to the process stakeholders, and the specific role that ICT plays in earning competitiveness. In the case of healthcare, there are core, enabling, (supporting) and other business processeses as well. Upon thoroughly examining the enabling processes of a hospital, namely Patient Transport Logistics (PTL)[13], OR-WPS[14], and Central Sterile Services Department (CSSD) or Medical Supply (MS)[15], it would be evident that their contribution in enabling a well-functioning core process, which is the healthcare treatment of a patient, is remarkably significant[16,17]. For instance, as shown in figure (1.2), the total contribution in a typical German hospital is approximately €7.5 million or 3.5% of the total annual budget[18].

As costs are part of the competitive advantage, a few examples from the available data can be used for illustrative purposes. According to a report from The Commonwealth Fund[19], the cost of appendectomy in the United States is $13,851, whereas it is $4,408 in the United Kingdom. A heart bypass surgery costs $73,420 in the United

[10] Source: Vasco Eiriz et al. (2010) A conceptual framework to analyse hospital competitiveness [EBF10]

[11] Source: Ramírez Pérez et al. (2021) Information and Communication Technologies as a competitive performance factor in provider institutions of medical services in Ensenada, Baja California [RLTMV21]

[12] Source: Ibid

[13] In German: Patiententrasnportlogistik (PTL)

[14] In German: Personaleinsatzplanung im OP-Bereich (OP-PEP)

[15] In German: Schrankfachversorgung (SFV)

[16] Note: Based on values collected in the Benchmarking of Logistical Support and Service Processes in Healthcare and Industrial Applications (BELOUGA) project

[17] Source: Herbert Woratscheck et al. (2015), Wertschöpfungsorientiertes Benchmarking [Wor+15a]

[18] Source: Ibid - Woratschek et al.

[19] Source: The Commonwealth Fund (2014), How can the U.S. get health care costs under control? [The14]

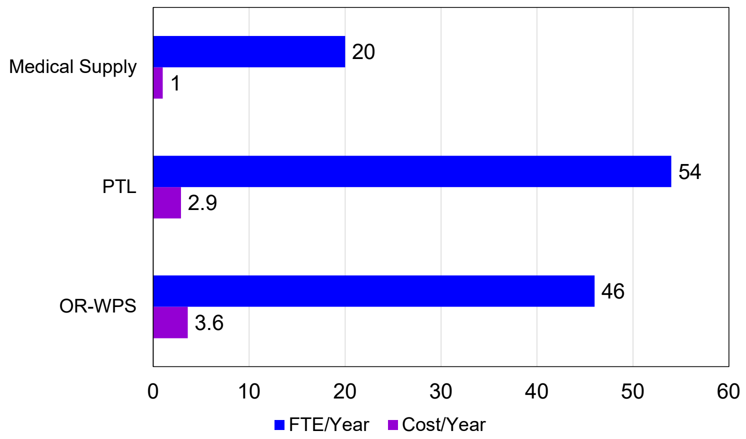


Figure 1.2: Share in terms of the annual budget and different enabling (supporting) business process of core (primary) process. Also shown is an average number of staff needed for these enabling processes among the surveyed German hospitals.

States but $14,437 in The Netherlands. Owing to market conditions, the prices of treatment may vary among the various states and hospitals in the United States. The cost of an MRI in Hospital A in New Hampshire is approximately $524 as compared to $3,918 in another hospital designated Hospital B. The primary reason for this variation is the manner in which a healthcare provider strategically positions itself in the market, the types of services provided, and their cost structure, customers, and competitors. The pie chart on the left side in figure (1.3) illustrates the breakdown of total (gross) hospital costs in 2018 by individual cost type in Germany. Approximately 19.4 million patients were treated as full inpatients in hospitals in 2018. The adjusted costs per treatment case amounted to an average of €4823[20]. According to the report, large hospitals with 800 or more beds incurred the highest adjusted costs per case of treatment, averaging €5966. Hospitals with 200–299 beds and 300–399 beds reported the lowest adjusted case costs, which are €4277 and €4278, respectively.

At €66.5 billion, personnel costs accounted for 61.5% of total hospital costs in 2018 (excluding costs of advance education centres). The chart on the right side in Figure (1.3) shows their distribution among the individual employee groups. Medical service and nursing service together accounted for a share of 62% of total personnel

[20]Source: Gesundheit, Kostennachweis der Krankenhäuser, Fachserie 12 Reihe 6.3, Statistisches Bundesamt

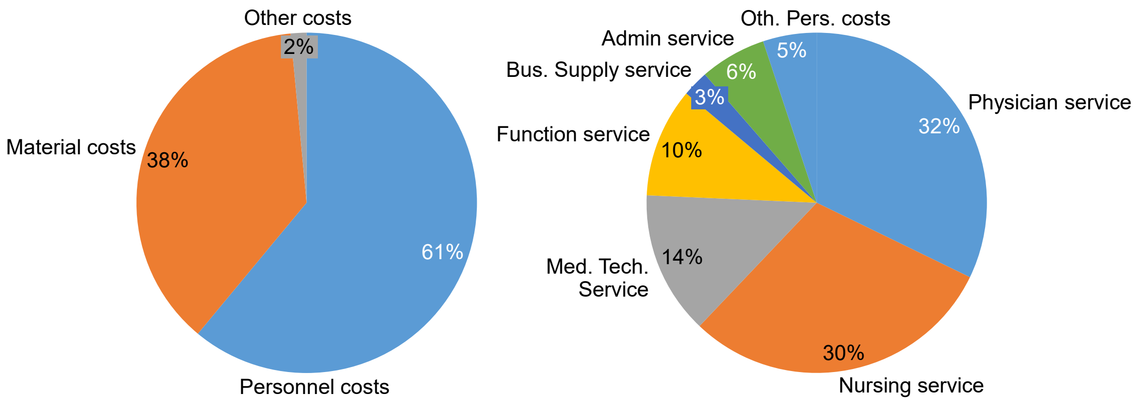


Figure 1.3: Excerpts of Hospital Cost (2018) based on data reported by the Federal Statistical Office of Germany report

costs. Notably, the group of available services includes, for example, nursing workforce (staff) for the surgical service and anaesthesia.

A remarkable theme in healthcare services is the competition to hire skilled human resources and retain them for efficient ORs at hospitals. Andrews et al.[21] found that the specific shortage of nursing personnel is not unique to the USA but widespread in developed nations. Owing to increasingly high work pressure, hospitals are becoming unattractive for nursing personnel to continue their work. Moreover, the COVID-19[22,23] pandemic has exacerbated the future shortage of healthcare workforce issues. Bohlken et al.[24] reported a review of the studies on stress and mental health of the frontline workers. According to a survey conducted in April 2021 by DGIIN[25] among nearly 1,321 respondents, 31% of non-physician employees in intensive care units (ICUs), emergency rooms (ERs), and ambulance services (OPDs) intend to quit

[21] Source: Diane Andrews et al. (2005) The nurse manager: job satisfaction, the nursing shortage and retention [AD05]

[22] Coronavirus disease (COVID-19) has been the worst infectious disease pandemic after Spanish flu given its impact on human well-being in terms of the number of infected persons, leading to numerous deaths worldwide. According to the data from Worldometer on October 25, 2022, officially, there were approximately 633 million infected (or tested positive) individuals and over 6.5 million deaths. In Germany, 35 million were infected, and over 152 thousand died; by contrast, in the USA, these numbers were 99 million and 1.09 million, respectively.

[23] Source - Worldometer: A reference website that provides real-time statistics on several topics of public interest, https://www.worldometers.info/coronavirus/?

[24] Source: Jens Bohlken et al. (2020), COVID-19-Pandemie: Belastungen des medizinischen Personals [Boh+20]

[25] DGIIN: German Society for Internal Intensive Care and Emergency Medicine

their employment in the next 12 months[26]. They concluded that in several departments of the hospitals, interventions would be needed to treat mental health issues. Similar studies have been underway in other countries such as China and USA. In Germany, according to a survey published by Krankenhaus Barometer[27] in 2019, there is a significant problem in hiring qualified and skilled nursing staff for intensive care units, as shown in figure (1.4)[28]. Additionally, an average of 7 nurses would be needed in an intensive care unit. According to another study by Zhang et al.[29] focusing on the USA's registered nurse (RN) supply and demand for 2016–2030, there will be shortages of approximately 154,018 RNs by 2020 and 510,394 RNs by 2030.

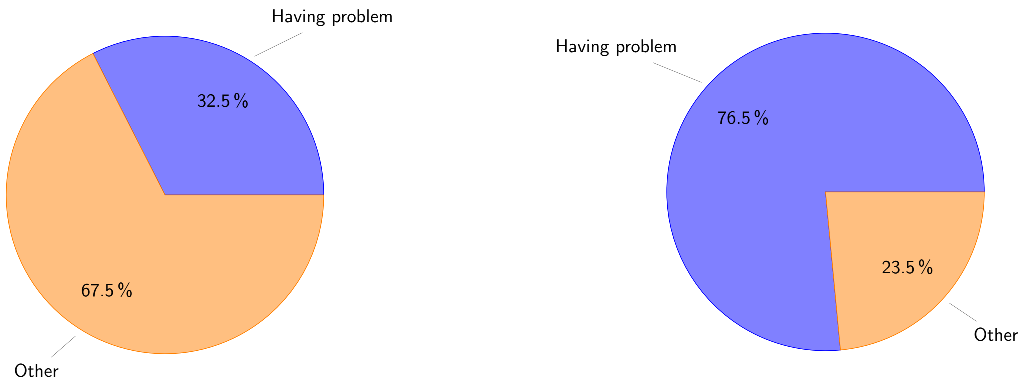


Figure 1.4: Percentage of German hospital reporting problems in hiring staff for intensive care units in left (the year 2011) and right (the year 2019)

From this perspective, the enabling processes, such as the OR-WPS, their current state, and how a decision-support system could reinforce the competitiveness of the hospitals are worth investigating. Therefore, the growing tendency for the adoption the role of technology and digitalisation in healthcare is focused on in section (1.1.2).

[26] Among physician employees, the figure is quoted to be 19%. In addition to these figures, 46% of non-physician employees and 30% of physicians plan to reduce their full-time job. For 77% of the non-physician and 68% of the physician employees, the stress during the COVID-19 pandemic influenced the decision. Moreover, 100% of the non-physician and 99% of the physician employees in ICUs believe that a sustainable hospital reform with the strengthening of intensive care and emergency medicine and better working conditions is indispensable.

[27] Source: Deutsches Krankenhaus Institut (2019), Krankenhaus Barometer [Deu19]

[28] Adapted from a pie chart by Henri Menke (https://texample.net/tikz/examples/pie-chart-color/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

[29] Source: X. Zhang et al. (2018), United States registered nurse workforce report card and shortage forecast - A revisit [Zha+18]

1.1.2 Medical and Technological Advancements

This section provides a background on why there is an ever-growing priority on technological advancements and their application in the healthcare domain and on the business processes, such as OR-WPS, supporting the delivery of healthcare needs[30]. As in every other domain, healthcare also encounters innovations in how new and (un)tested technologies might redefine its service delivery to the patient. An umbrella term coined to combine these aspects, similar to Industry 4.0, is Healthcare 4.0. According to Chanchaichujit et al.[31], embracing these emerging technologies will include Internet of Things (IoT) and wearable gadgets, blockchain, Artificial Intelligence (AI), big data and mobile applications. The concept of Hospital 4.0 could integrate the six-core principles proposed by Qin et al.[32]: interoperability, decentralization, virtualization, modularity, service orientation and real-time capabilities.

In a healthcare system, a mix of large, medium, and small hospitals run by private, public, or charities staffed by various medical and non-medical professionals deliver healthcare services. In the 21st century, and particularly in the past decade, digitalisation has been mostly ubiquitous, through various avenues such as smartphones, social media, the internet, and digital government or private service offerings. Hospitals have been no exception. Along with other industries, healthcare is also undergoing digital transformation but in a relatively slow pace[33]. Digitalisation as a theme can be helpful in hospitals grappling with increased competition and making significant progress through medical and technological advancements. As digitalisation is broad and can be an in-depth topic of discourse, specific areas of healthcare services that would practically benefit from digitalisation must be delineated. There are already many areas of services that are already using digital means to create value in healthcare. Hospitals use various software applications, mobile applications, real-time systems, advanced medical instruments, and other pieces of technology to support their business (healthcare) processes digitally. In this study, the theme was the further

[30] This work does not focus on innovation in healthcare delivery, such as disease diagnosis and patient treatment.

[31] Source: Janya Chanchaichujit (2019), An introduction to healthcare 4.0 [Cha+19]

[32] Source: Jian Qin et al. (2016), A categorical framework of manufacturing for industry 4.0 and beyond [QLG16]

[33] Source: Jochen Baierlein (2017), Grad der Digitalisierung im Gesundheitswesen im Branchenvergleich – Hinderungsgründe und Chancen [Bai17]

digitalisation of decision support for advancement to the next level by using computer simulation. In the 90s, Bucklin et al.[34] proposed to disrupt the marketing domain by moving from decision support to decision automation. While the human factor may set healthcare apart, it is disrupted by ideas similar to those proposed by Bucklin et al.

Within hospitals, the ORs are the most cost-intensive and potentially attain a viable profit proposition. The ORs will also undergo continual digital transformation due to technological advancements. Recent advances in three areas—the processing power of computers, ultra-fast communication with optical fibre and 5G[35], and the availability of a large amount of data (Big Data)—may offer digital transformation opportunities to the ORs planning and scheduling (predictive) analytics. A computer simulation can afford intraday, daily (i.e. for the day ahead), weekly, monthly, or even yearly predictions for any scenario for a given workforce and ORs available to conduct the surgeries. Significant (historical) data can facilitate training of the simulation models. Compared to other domains, in healthcare, before a final decision via digital means is made, it is wise to keep Human-In-The-Loop (HITL) to ensure that a patient's life is not at risk. The successful adoption of these technologies can motivate the automation of the decision-making process in other use cases in healthcare service providers.

The ongoing COVID-19 pandemic could be once-in-a-century extreme case wherein the global economy and healthcare systems are extraordinarily stressed. Nevertheless, it presents a new opportunity to improve our understanding and accept new research opportunities in process improvement and application of information technology in High-Reliability Organization (HRO) such as hospitals. The fight against the COVID-19 pandemic has positively contributed to the broader benefit of digitalisation at workplaces, educational institutions, homes, and public places. With regard to OR-WPS in particular, Lerzynski[36] has identified that human (workforce) resource planning can be a promising area to apply digitalisation and is worth exploring.

[34]Source: Randolph Bucklin et al. (1998) From decision support to decision automation: A 2020 vision [BLL98]

[35]Note: 5G is the 5^{th} generation technology standard for broadband cellular networks.

[36]Source: Guido Lerzynski (2022), Hospitals of the future: how can we get there? [Ler22]

1.2 Research Problem

On the basis of sections (1.1.1) and (1.1.2), which provided direction for the research work, the research problem and questions formulated for further investigation are described here and the following sections, (1.3) and (1.4). As in any business domain, a healthcare service provider such as a hospital has core (primary) and enabling (supporting) business processes. All core processes directly deliver value to a customer, such as a *hospital patient*. The enabling processes are essential to run a core process and indirectly contribute to the overall hospital performance in terms of productivity, quality, and cost, according to Laguna[37]. As the ORs are the most costly to run, the scarce skilled medical workforce is needed to support their continuous operations. On the basis of this statement and the motivations described in section (1.1), it can be concluded that enabling (or supporting) a core (or primary) is not a well-researched topic. A preliminary literature review prior to this research study revealed that the OR-WPS is one such topic for which in-depth studies are lacking[38]. Therefore, in this study, the focus was on the OR-WPS process area and its computer simulation. The following section (1.3) presents the research questions (RQs) that this study sought to address.

1.3 Research Question

In view of the goal of the thesis, a high-level research question of this work is as follows:

> *(Central) RQ: Can a computer simulation reinforce itself as a research method to better understand and improve the healthcare business process?*

On the basis of the central research question, the following sub-questions arise and must be eventually addressed in this study:

[37] Source: Manuel Laguna (2011), Business process modeling, simulation and design [Lag11, p. 74-75]

[38] Note: There is a difference between *workforce scheduling* from *case scheduling* because workforce scheduling focuses on personnel, whereas case scheduling begins with medical procedure requests, including personnel skill requirements to conduct a medical procedure.

RQ1: Which is the most suited computer simulation method to fulfil the needs of this study?

RQ2: How can a multi-agent simulation of OR-WPS be practically implemented and in which manner can it act as a decision support system?

RQ3: Which approach is suitable to create the statistical models of simulation input within a typical hospital, and how can it contribute to current research gaps in input modelling?

RQ4: What are the essential differences in the results between the surveys conducted among OR-WPS stakeholders at the hospitals in Germany and USA?

RQ5: What insights can be gained from the qualitative data collected during the OR-WPS process discovery? What are the critical differences between the results of this analysis and the survey outcomes?

(Advanced) RQ: How can an Enterprise Architecture (EA) framework support the introduction of computer simulation and help an enterprise manage its transformational IT landscape?

The following section (1.4) discusses the research process for this study, specifically the challenge of accommodating methods from different domains given the interdisciplinary nature of this study.

1.4 Research Process

In general, this work follows the Design Science Research (DSR) research process by Peffers et al.[39] as shown in figure (1.5). Peffers et al. divided the research process into six steps, namely, (1) problem identification and motivation, (2) objectives of a solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. Step 1, which is *problem identification and motivation* phase, entails

[39] Source: Ken Peffers et al. (2007), A design science research methodology for information systems research [Pef+07]

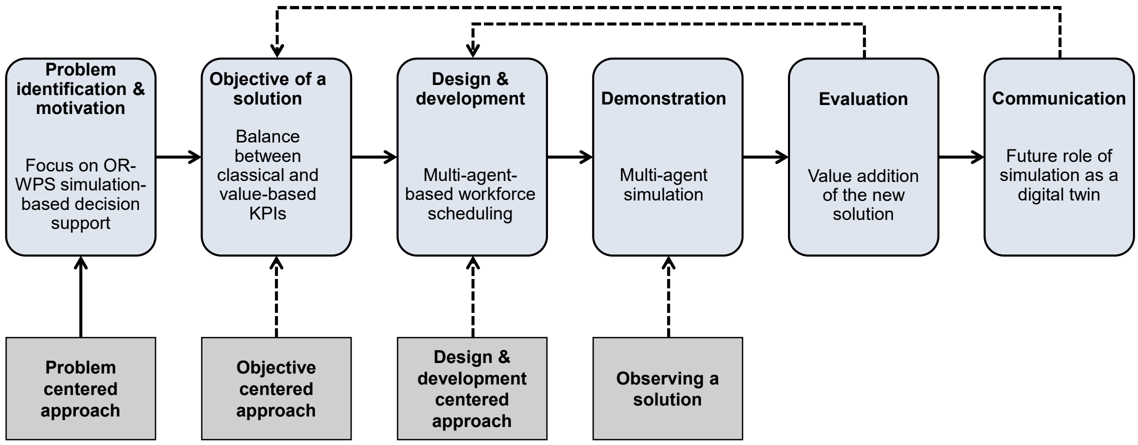


Figure 1.5: Design science research process (DSR) followed in this work

the gathering of inputs from motivation (1.1), research problem (1.2), and research questions (1.3). In the step 2, the identified requirements from the previous step would be the inputs to the *objectives of a solution*. The step 3 would be used to realise the *design and development* of an artefact. Following the steps of Peffers et al., in step 4, the goal of the demonstration would be to show that the artefact satisfactorily serves its intended purpose and realises the sought functions. In step 5, after the demonstration, the actual evaluation takes place. Its use of operationalised measures distinguishes it from other steps. The artefact will be compared to other artefacts that solve the same problem throughout the evaluation. It is only helpful if the newly formed artefact affords more scientific benefits than a prior solution. The final step, step 6, entails the publication of a scientific study focused on its communication.

This study employed methods from computer science, social science, business administration, and operations research. A hybrid approach comprising both quantitative and qualitative methods was employed in this study. Usually, in applied science, a *computer simulation*, which is a quantitative method, receives numbers as input (quantitative data) for a simulation model (usually a complex mathematical equation) to produce numbers (quantitative results) as output for further interpretation. It is also a well-established method of scientific enquiry. Given the nature of the problem at hand, instead, to solve a complex mathematical equation in a simulation, this study employed a *multi-agent* simulation. The aim in this approach would be to understand if the agent's behaviour can be programmed, imitated, and the results understood. The goal must be to develop a simulation model, propose theories based on this model, and form hypotheses. On this basis, section (1.5) provides an overview of the thesis organization.

1.5 Overview of the Thesis

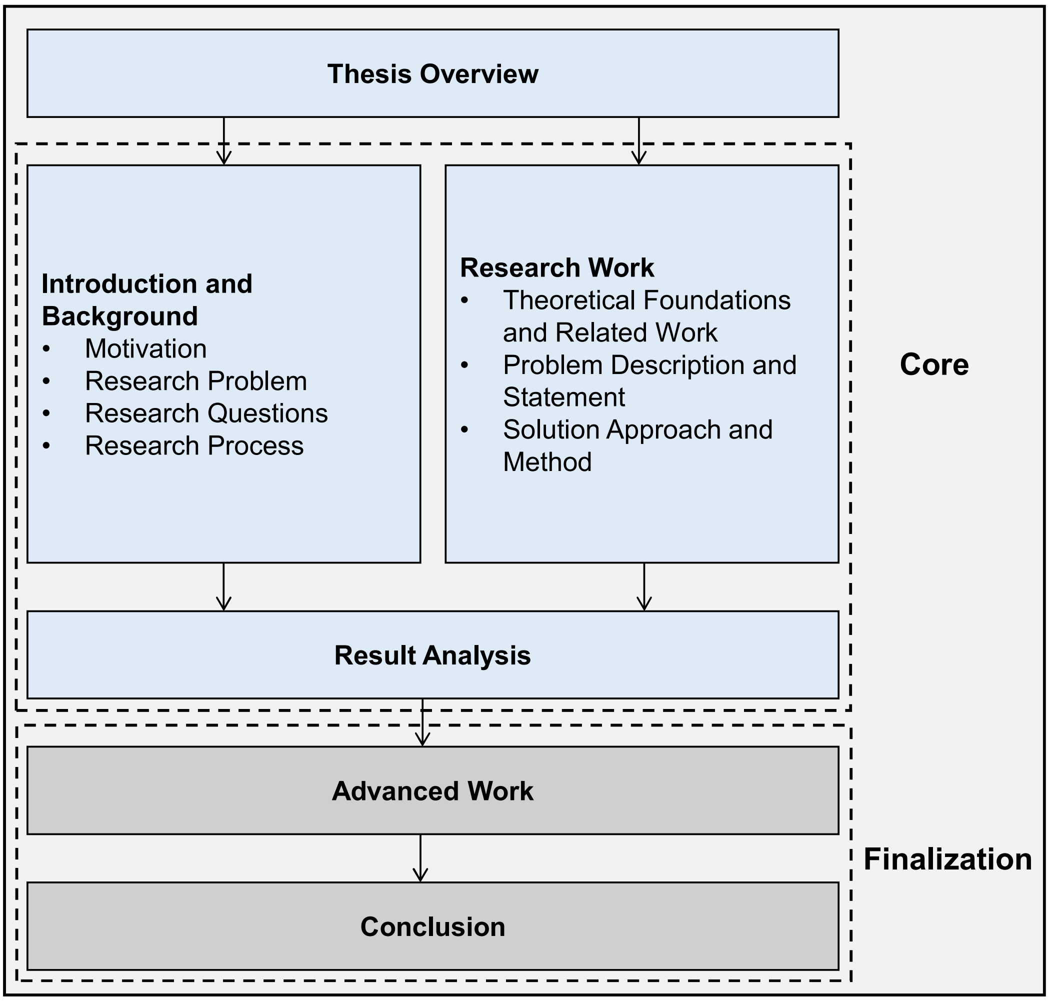


Figure 1.6: Structure of the thesis report

This thesis is organised into chapters, as shown in figure (1.6). The chapters (1), (2), (3), (4) and (5) form its core, whereas chapters (6) and (7) serve to finalise the work. Chapter (2) presents the fundamental concepts and those specifically relevant to this study; it essentially summarises the essential knowledge required to comprehend the contents of this thesis. Theories related to computer simulation, input-data modelling, and experimentation relevant to this work are briefly introduced with references for in-depth readings. Further, the literature concerning the application of multi-agent simulation technology in healthcare services with a focus on ORs is summarised. Moreover, evidence supporting the application of concepts such as Agent-Based Modelling & Simulation (ABMS) or Multi-Agent System (MAS) is presented given the overlapping interests with this study. The quantitative and qualitative data analysis methods and techniques, which are widely used in industrial engineering[40] and in social science[41], were applied in this study. Therefore, their applications in similar research work elsewhere are also described in this chapter. Chapter (3) focuses on why OR-WPS must be focused on and its manifestations in German and American hospitals in particular. The sections present the case-of-action to study the enabling process of healthcare service providers in more detail. The chapter also introduces why (only) specific solutions from one type of domain cannot be applied but rather a multidisciplinary method can be more valuable to solve the current optimisation problems of the enabling process of ORs.

Chapter (4) introduces the different approaches and methods adopted in this study to address the RQs. The description of software architecture design, implementation, validation, and verification details are included. Chapter (5) presents the results of analysing OR-WPS from six different perspectives. These include Semi-Systematic Literature Review (SLR), business process discovery, ABMS or MAS, work sampling, (international) customer survey, and content analysis. The sections include the various conclusions drawn as well as the advantages and limitations of the method and results. Essentially, it presents the evidence that the healthcare service providers can use information technology and its data sources from different fields to support operational business-process decision-making in the future. Computer simulation based on multi-agent technology to create a Digital Twin (DT) of the OR-WPS is presented as a logical choice for further research. The last two chapters, (6) and (7), combine the *finalisation* part of this work. The objective of the chapter (6) is to introduce how EA

[40] In German: Wirtschaftsingenieurwesen
[41] In German: Sozialwissenschaft

will help address the research problem in a rigorous step-by-step approach to answer the why, what, how and with-what questions. Finally, chapter (7) focuses on presenting conclusions of this work followed by the implications of the results, possible future research direction, its prospects, and concrete proposal.

2 Theoretical Foundation and Related Work

Abstract: *This chapter presents the fundamental as well work-relevant theoretical concepts. A brief introduction to computer simulation as the third pillar of scientific research is provided, followed by its different approaches to business administration. The concepts relevant to this study—including OR-WPS, its customers, its performance measurement and the vision for applying EA in this study—are covered. Relevant definitions and brief explanations are also provided. In addition, a brief introduction to the quantitative and qualitative techniques used for identifying, collecting, analysing and interpreting the OR-WPS data is within the scope of this chapter.*

2.1 Fundamental Concepts

This chapter introduces a few concepts essential to understanding the subsequent chapters. A PTL enabling business process is an example of a *value chain*[1], whereas an OR-WPS is that of a *value network*[2]. These concepts are briefly described in Section (2.1.1). It is followed by a brief introduction to business process and performance management in Section (2.1.2). A brief background of computer simulation as the third pillar of science and various approaches for its application in business administration are provided in Section (2.1.3). The concept of managing a simulation experiment is introduced in Section (2.1.4). An approach to appropriately manage a business transformation, given that the enterprises and their information technology (IT) landscapes are generally becoming exceedingly complex, is provided in Section (2.1.5).

[1] Source: Franziska Jehle et al. (2015), Benchmarking-Studie Patiententransportlogistik (PTL) [Jeh+15]

[2] Source: Stefan Hastreiter et al. (2015), Benchmarking-Studie OP-Personaleinsatzplanung [Has+15]

2.1.1 Value Chain, Value Network, and Value Shop

Value addition is one of the cornerstone concepts. Generally, *value* is intangible but widely referred to in everyday life. People refer to the *intangible* value of owning a car or a house and while discussing any service, such as a call centre, a consulting company, or even a hospital. On the basis of the concept of value, consumers usually pay for a product or service more than the combined cost of material resources required to create that specific product. Porter[3] proposed the ground-breaking concept of *value chain*[4], as shown in figure (2.1), which is evidently applicable in case of tangible items, such as car manufacturing, or simplified services wherein a small number of workers add value in a chain.

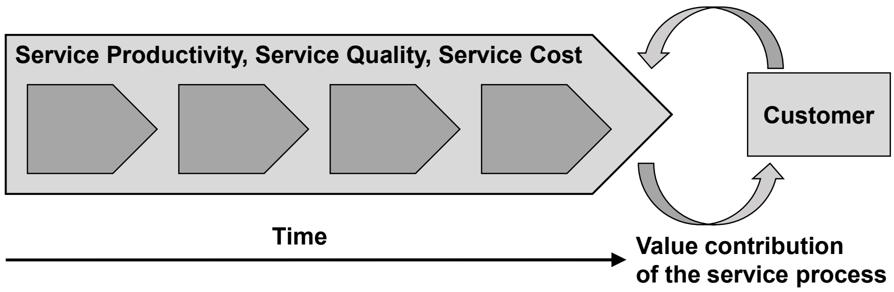


Figure 2.1: A simplified value chain view (based on one of the outcomes of BELOUGA project) transforms inputs into products for a customer. A chain is composed of a pooled or sequential value addition from beginning to end. The customer experiences a service.

The business processes (and activities) in the value chain can be primary (core) or secondary (supporting or enabling), and each type contributes differently to value addition. The primary process in healthcare is the provision of medical consultancy or treatment to a patient, and the value is patient *well-being*. The secondary healthcare process is the transportation of a patient from one location to another, either from home to hospital or within a hospital, so that the consultancy or treatment can be delivered to a patient. The other categories that characterise the value chain are

[3]Source: Michael Porter (1985), Competitive advantage - Creating and sustaining superior performance [Por85]

[4]Note: There is another concept referred to as *value stream*, which is the sequence of activities—from the first request from the customer to the receipt of benefit—that contribute value to the end customer. It is a concept that originated in *lean manufacturing*. Although value chain and value stream are different concepts, they occasionally overlap.

logistics, marketing and service, and their crucial cost drivers are economies of scale and capacity utilization.

The drawbacks of applying the value chain concept on many domains were highlighted by Stabell et al.[5]. They proposed two additional concepts, namely *value network* and *value shop*, and argued that the value chain concept is less suitable for analysing the service domain. The value shop uses technology to solve a customer or client problem. A value chain entails a sequence to mass produce a conventional product, whereas a value shop organises operations. It assigns resources in a structured and relevant manner to suit the customers' needs. Domains such as healthcare, EA, and most engineering disciplines are examples of value shops delivering services to customers. The key value driver is reputation; the primary activities are identifying problems, solving them, selecting the right solution, executing that solution, and performing control. This is illustrated in figure (2.2).

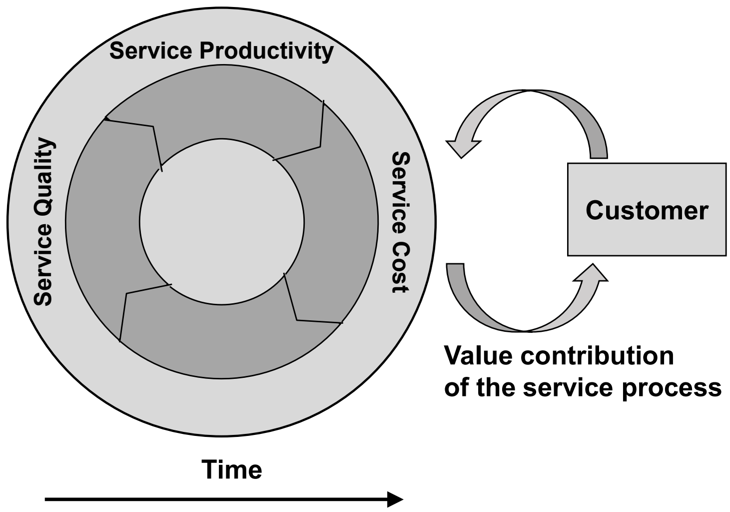


Figure 2.2: A simplified view of a value shop (based on one of the outcomes of BELOUGA project) transforms inputs into services for customers. A shop is composed of a pooled, sequential, or reciprocal value addition from a cyclic or spiralling configuration.

Suppose an enterprise in a domain can be modelled as a value network. Then, it is

[5]Source: Charles Stabell et al. (1998), Configuring value for competitive advantage: on chains, shops, and networks [SF98]

dependent on *mediating technology* to provide services to its customer, as shown in figure (2.3). Classical banks, electricity retailers, and modern internet-based companies using the *sharing economy* are examples of value networks. The key cost drivers of value networks are scale and capacity utilization, whereas their primary activity categories include network promotion, managing contracts, and providing infrastructure operation to their customers. To perform an optimum analysis of the value delivered to the customers by the enterprise, different value configurations (i.e. chains, shops, and networks) must be considered in order to identify the suitable configuration type. This approach can also be applied to business processes.

A customer can be *internal* or *external* to the firm under consideration. Detailed studies concerning these value configurations were performed by several scholars, such as Woratschek et al.[6] and Woiceshyn et al.[7].

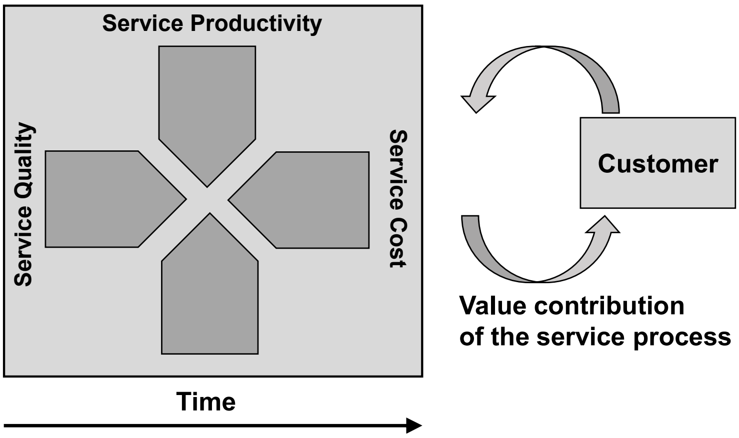


Figure 2.3: A simplified view of a value network (based on one of the outcomes of BELOUGA project) transforms inputs into a customer's services. A shop is composed of a pooled or reciprocal value addition from/in a simultaneous or parallel configuration.

As indicated by the concepts of value chain, value shop, and value network, classical approaches wherein multiple entities are compared are inadequate for evaluating

[6]Source: Herbert Woratschek et al. (2007), Ansätze zur Analyse von Wertschöpfungsprozessen – Eine theoretische und empirische Betrachtung der Besonderheiten bei Dienstleistungen [WRS07]
[7]Source: Janna Woiceshyn et al. (2008), Value creation in knowledge-based firms: Aligning problems and resources [WF08]

processes in the service area. Benchmarking itself is a well-defined term and was proposed by Camp[8]. Particularly in the service industry, the service provider's perspective is considered in traditional benchmarking, independent of the interfaces and other stakeholders involved in the service process. As a result, value-based benchmarking broadens the traditional, more cost- and performance-focused benchmarking to include a customer-oriented value perspective and concentrates on the service's primary value-added activities.

2.1.2 Value of Business Process and Performance

A healthcare service provider, typically a *hospital*, is a medical institution that provides consultancy, treatment and (occasionally) research support for the benefit of society[9,10]. A hospital employs medical staff including surgeons, physicians, and nurses and has the necessary medical equipment for the staff to perform diagnostic procedures and treatment. Physicians who are allowed to perform surgery and administer anaesthesia are referred to as *surgeons* and *anesthesiologists/anaesthetists*, respectively[11]. For most surgeries, a minimum number of medical professionals are needed; therefore, workforce (or staff) scheduling is a dominant concept that impacts the overall productivity of ORs. *Workforce scheduling* can be defined as in definition (2.1); this is also applicable to other workgroups such as nurses.

Definition 2.1. *Workforce Scheduling*

> *"Staff scheduling is the process of deciding which anesthesia providers work each shift on each day." [MDE06, p. 1500]*

ORs refer to the facilities wherein surgeries are performed; both workforce and patients are to be scheduled for ORs. Therefore, the concepts of *elective* and *outpatient*

[8] Source: Robert C. Camp (1989), The search for industry best practices that lead to superior performance [Cam89]

[9] Note: This work focuses on hospitals that are either academic (in the USA) or secondary (II) care-level (in Germany).

[10] In German: II. Versorgungsstufe

[11] More information on the actors/agents in the ORs: Christoph Niemann (2012), Hybride Entscheidungsunterstützung in partiell automatisierbaren Entscheidungssituationen [Nie12, p. 26-29]

are of tremendous importance. As reported by McIntosh[12], the elective-case patients can wait more than three nights, whereas outpatient patients do not stay overnight in the hospital.

Historically, academicians and practitioners have contributed to the business process "management" field. In 1776, Adam Smith described the business process for a factory. Other prominent scholars who contributed to this field include Frederick Winslow Tylor, Peter Drucker, and Thomas Davenport. A clear understanding of the underlying "business process" is essential; otherwise, building of simulation software tools, their effective operation, and delivering the appropriate output to the process stakeholder cannot be accomplished. The processes in an enterprise, according to Rummler et al.[13], can also be classified as generic primary (core) processes[14], industry-specific primary (core) processes[15], generic enabling (supporting) processes[16], and generic management processes[17]. Thus, the question arises as to what the precise definition of a process is. The theoretical definition of business processes by Sharp and McDermott (2009), provided in (2.2) and used in this work, delineates the relationship between activity and triggering events and will potentially aid the development of business process simulation models.

Definition 2.2. *Business Process*

> *"A business process is a collection of interrelated activities, initiated in response to a triggering event, which achieves a specific, discrete result for the customer and other stakeholders of the process." [SM 2, p. 56]*

Other examples of the processes of healthcare service providers such as hospitals include emergency department (ED) operations and medication administration. Im-

[12]Source: Catherine McIntosh et al. (2006), The impact of service-specific staffing, case scheduling, turnovers, and first-case starts on anesthesia group and operating room productivity [MDE06, p. 1500]

[13]Source: Geary Rummler et al. (1995), Improving performance - How to manage the white space on the organization chart [RB95]

[14]Note: Business development, product or service development, manufacturing, distribution, billing, order fulfilment, customer service, and warranty administration.

[15]Note: Grant allocation in government or loan processing in banking.

[16]Note: Formal strategic and tactical planning, budgeting, recruitment, training, facility management, purchasing, information management.

[17]Note: Strategic and tactical planning, goal setting, resource allocation, human performance management, operations review performance monitoring.

portantly, processes exist at different hierarchies/levels and must be rigorously identified so as to avoid any ambiguity. The process hierarchy for enterprise processes can be described using various frameworks such as BP Trends, ARIS hierarchy, Value Creation Hierarchy, Generic BPM hierarchy, eTOM model, SCOR hierarchy, and APQC hierarchy. An integrated but straightforward pyramid-form-model of the core, enabling, and management processes in a hospital inspired by Gadatsch[18] is illustrated in figure (2.4). At the base of figure is the core process of administration of patient (external customer) up to cost settlement. In the middle are enabling (supporting) processes such as information technology, which also include other supporting processes such as patient transport or timely delivery of surgical equipment. The management processes are shown at the top.

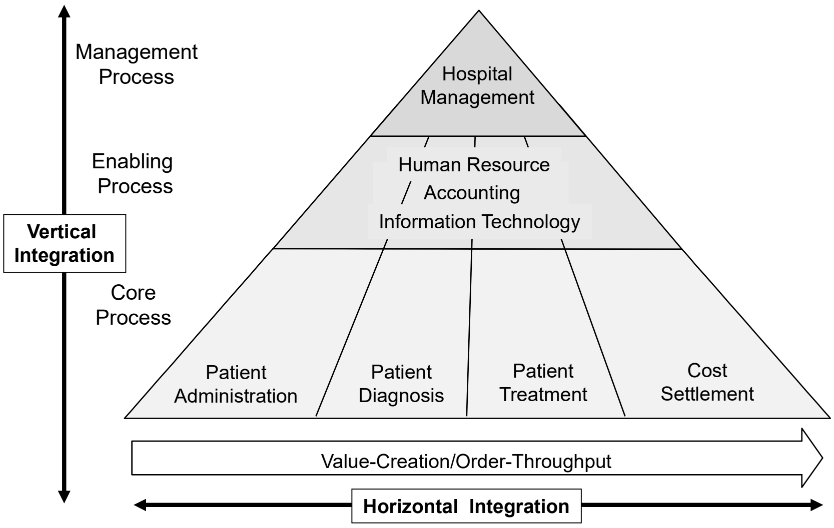


Figure 2.4: Role of computer modelling and simulation in the overall problem solving of the underlying business process (own illustration based on Gadatsch)

Business process control is a discipline of management that focuses on measuring process *efficiency* and effectiveness. A Performance Management (PM) system sets the context and the benchmark of a (business process) *performance*[19]. The performance is defined based on the objectives and targets achieved by the actions of the components in a system; performance measurement, which is a well-developed

[18] Source: Andreas Gadatsch (2013), IT-gestütztes Prozessmanagement im Gesundheitswesen [Gad13b]

[19] Source: Michel Lebas (1995), Performance measurement and performance management [Leb95]

field of management, can be used to aid a business entity in operationalising the controlling processes[20]. An appropriate control also minimises any unforeseen *business risks* concerning aspects such as escalating costs, unmotivated workforce, deviation from agreed business process, and drop in productivity. The applicability of relevant elements of PM was examined in this work on the basis of computer simulation-based *measurement* to address the following questions:

(a) What can be an excellent approach to create a performance measurement system suitable for the computer simulation of business processes?

(b) How are the selected measurement and overall process strategy in alignment?

(c) Which characteristics distinguish an excellent key performance indicator (KPI) to be selected for this work?

2.1.3 Value Addition via Computer Simulation for Decision Support

Since the publication of the works by Simon[21], Winsberg[22], and, recently, Durán[23], there has been increasing interest in the application of computer simulations to address problems in natural science, social science, and engineering. The advantages of using simulations include potential savings in investment and increased profits as well as the scope to experiment without the limitations of an actual system. Focusing mainly on fundamental problems in business administration[24], Pidd[25] provided an overview on the application of *system dynamics* (SD)[26]. Further, *discrete-event simulation* (DES)[27,28], and *agent-based modelling and simulation* (ABMS)[29,30] have

[20] Source: Stefano Tonchia et al. (2010), Performance measurement [TQ10]
[21] Source: Herbert Simon (1996), The sciences of the artificial [Sim96]
[22] Source: Eric Winsberg (2009), Computer simulation and the philosophy of science [Win09]
[23] Source: Juan Durán (2018), Computer simulations in science and engineering [Dur18]
[24] Note: Business administration is considered a part of management science, dealing with managing a firm.
[25] Source: Michael Pidd (2004), Computer simulation in management science [Pid04]
[26] In-depth source: John Sterman (2000), Business dynamics - Systems thinking and modeling for a complex world [Ste00])
[27] In-depth source: Carson Banks et al. (2010), Discrete-event system simulation [Ban+10]
[28] In-depth source: Christos Cassandras (2008), Introduction to discrete event systems [CL08]
[29] In-depth source: Nigel Gilbert (2008), Agent-based models [Gil08]
[30] In-depth source: Michael North et al. (2007), Managing business complexity - Discovering strategic solutions with agent-based modeling and simulation [NM07]

been explored. The various aforementioned approaches can be broadly classified based on *abstraction* and *continuum*, as shown in figure (2.5)[31]. Law et al.[32] as well Robinson[33] described procedures to conceptualise, implement, and apply the various approaches to modelling business problems. A working definition of the *computer simulation*, as referred to in the following chapters, is provided in definition (2.3).

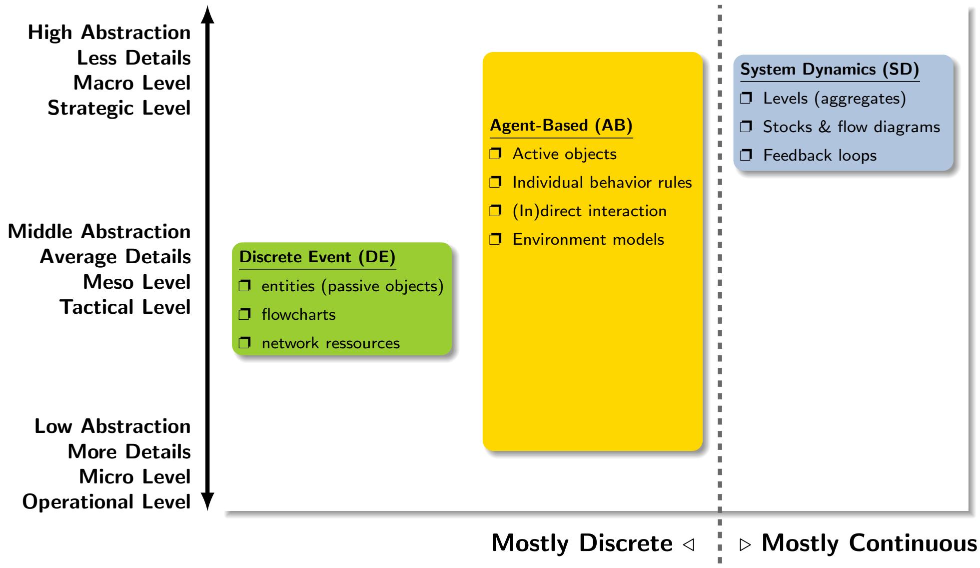


Figure 2.5: An overview of the common simulation approaches to solving problems in business administration, based on their suitability at various levels of abstraction

Definition 2.3. *Computer Simulation*

> *"A simulation is an imitation of a system and its dynamic when it progresses through time." [Rob04, p. 2]*

A simulation can be *deterministic* vs *random* or *static* vs *dynamic*. A simulation utility is to imitate the physical reality, such as testing a model of a new aeroplane design using its computer model to optimise its weight, speed, and altitude of flying. Similarly to an experiment using physical objects, *simulation experiments* can be

[31] Simulation approaches versus abstraction levels by Valeria Borodin (https://texample.net/tikz/examples/simulation-abstraction/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

[32] Source: Averill Law et al. (200), Simulation modeling and analysis [LK00]

[33] Source: Stewart Robinson (2004), Simulation - The practice of model development and use [Rob04]

performed using models. For completeness, a working definition of Discrete-Event Simulation (DES) is provided by Fishman[34]. Another simulation approach, known as either ABMS or MAS, is used when DES is inadequate in modelling the underlying real-world phenomenon. The terms multi-agent and agent-based are used interchangeably herein, as their boundaries are blurred[35,36]. The definition of an *agent* and *agent-based modelling* is provided in definitions (2.4) and (2.5).

Definition 2.4. *Agent*

> *"An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to achieve its delegated objectives." [Wei13, p. 4]*

Definition 2.5. *Agent-Based Modelling*

> *"In agent-based modelling (ABM), a system is modelled as a collection of autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules." [Bon02, p. 7280]*

Bogg et al.[37] detailed the criteria for employing MAS. Other considerations include the architecture and organisation; agent communication; negotiation, bargaining, and coordination; demands concerning computational aspects; and the requirement for control and execution followed by optimisation. A theoretical description concerning the implementation aspects such as programming language and software engineering ABMS were described by Weiss[38]. A computer simulation can deliver value in all configurations, whether chain, network or shop, but interesting to apply in HRO to support the strategic/tactical/operational decision-making process. Therefore, a new

[34]Source: George Fishman (2001), Modeling, programming, and analysis [Fis01, p. 4]

[35]Note: “Agent-based” indicates the modelling of behaviours by following rules in order to analyse, make forecasts, and provide interpretation of the findings to describe reality, whereas “multi-agent” indicates the use of sophisticated communication among its agents, which interact to imitate reality.

[36]Note: A significant difference between a *software agent* and a *computer program* is that programs are written anticipating all the possibilities within its scope, whereas an agent may go beyond a computer program to decide for themselves the future actions to achieve their objectives.

[37]Source: Paul Bogg et al. (2008), When to use a multi-agent system? [BBL08]

[38]Source: Gerhard Weiss (2013), Multiagent systems [Wei13]

concept referred to as DT, which presents an integrated environment to perform simulation, has been proposed recently. A definition of DT is provided in (2.6), followed by a comparison between a computer simulation and a digital twin in table (2.1), indicating how these two concepts can complement each other in the future.

Definition 2.6. *Digital Twin*

> *"Digital twin can be defined as a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision making." [RSK20, p. 21980]*

Computer Simulation	Digital Twin
A method of scientific enquiry based on the reproduction of behaviour of a system	A vision refers to a broad physical and functional description of a system
Data required for validation of specific purpose	A data-driven virtual model of reality to mimic one-to-one
Applied and practised in research and the industry for two decades	Recent technology trends are leading to digital disruption in the industry
Generally based on one simulation model	Can be a well-integrated simulation model
Used in developing a system to support design tasks or validate properties.	Used in the operation of a system.

Table 2.1: Comparison of the two concepts - Computer Simulation and Digital Twin.

Enterprises decide on strategic, tactical, and operational levels on the basis of available information and then the various model implementations. Information technology serves an enabling function and aids corporations digitalise decision making. Decision Support System (DSS) is a type of information system, which essentially supports decision-making activities. Typically, healthcare is the focus of DSS; however, clinical decision support systems[39] are different from management decision support systems. Figure (2.6) depicts a simplified view of how a DSS can ideally hide the complexity of implementation and can provide guidance to manage business entities at different levels of abstraction of an enterprise. The DSS could be a business intelligence system based on data warehousing, data mining, business

[39]Note: For more information on clinical DSS - Source: Bonnie Kaplan (2001), Evaluating informatics applications - clinical decision support systems literature review [Kap01]; Source: Kathryn Hannah et al. (2007), Clinical decision support systems [HBB07]

analytics, and visualisation or one based on artificial intelligence, multi-agent simulation, or their combinations[40]. The relationship between a *computer simulation* and *decision support* was elucidated by Saam et al.[41]. Furthermore, Meierhofer et al.[42] recently proposed the modelling of decision support by using digital twins in business processes with a persistent focus on service value creation for the system's human actors. The aforedescribed developments signify that entanglement and harmonisation of the concepts in the literature have been occurring.

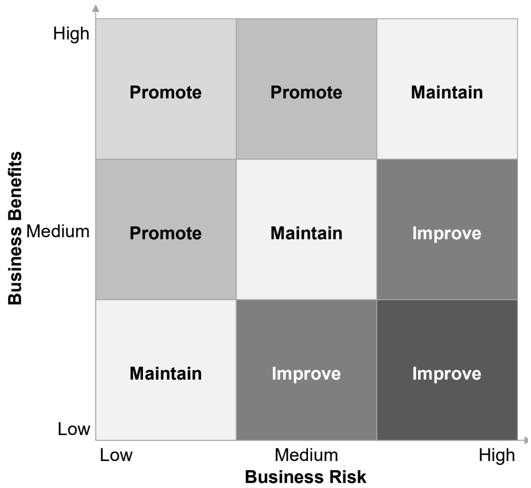


Figure 2.6: A simplified view of a decision support system dashboard. Here, business benefits versus business risks are plotted so that a management decision can be taken for any implementation at the strategic, tactical, or operational level.

2.1.4 Design of Simulation Experiment

The typical cycle entails modelling, simulation, and experimentation; however, real-world data are essential for validating a simulation and thus achieve its purpose. As illustrated in figure (2.7), which is adapted from an original figure from Gadatsch[43], a simulation model can be used for experimentation by using real-world data and obtain simulation results. On the basis of the obtained results, suitable changes can

[40] Note: The types mentioned here do not cover all types of DSS.
[41] Source: Nicole Saam et al. (2019), Simulieren und Entscheiden [SRK19]
[42] Source: Jürg Meierhofer et al. (2021), Digital twin based decision support services in business operations [MSS21]
[43] Source: Andreas Gadatsch (2013), IT-gestütztes Prozessmanagement im Gesundheitswesen [Gad13b, p. 99]

be implemented in the real-world business process or inputs to achieve *operational excellence*. Gadatsch[44] has stated that the objective of the simulation in practice could be to check the operational capability, validate the realism and plausibility of the model, and evaluate alternative process models.

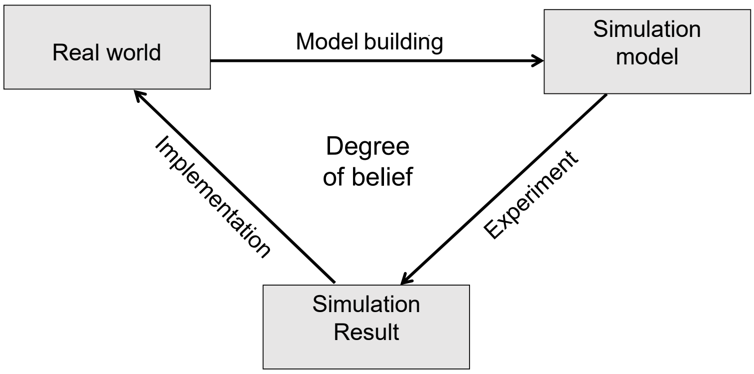


Figure 2.7: Role of computer modelling and simulation in the overall problem solving pertaining to the underlying business process

Complexities arise because of the multitude of factors in a simulation experiments. For example, suppose there are two factors with two levels, also written as 22 (or 2×2) producing (2^2 = 4) factorial points. There would be many inputs to a *simulation experiment*. In this regard, *design of experiment* (DOE) is suitable for maximising the objective function based on many combinations of inputs. A definition of DOE is as follows:

Definition 2.7. *Design of Experiments*

> *"Design of Experiments refers to the process of planning, designing and analysing the experiment so that valid and objective conclusion can be drawn effectively and efficiently." [Ant03, p. 7]*

Application of DOE principles is crucial in order to systematically analyse a simulation model[45]. To advance the design of the experiment to the next level, an approach

[44] Ibid

[45] Source: Iris Lorscheid et al. (2012), Opening the 'black box' of simulations: increased transparency and effective communication through the systematic design of experiments [LHM12]

using *augmentation* is of interest. *Augmented experiment* refers to an interaction between the *real world* and *simulated world* through communication devices such as *sensors*. A *real-world scenario* (best case, optimum case, or worst case) can be developed based on past experiments or no knowledge, and the actual world operations and simulation seamlessly provide feedback to each other in real time. The key performance indicators are tracked as part of the *measuring and monitoring*, as shown in figure (2.8). Better decision making can be accomplished by systematically devising a hybrid concept of the DOE and augmentation. The concept remains mostly theoretical, and only a few studies have been reported thus far. For example, augmented reality content has been employed in preschools[46] for learning.

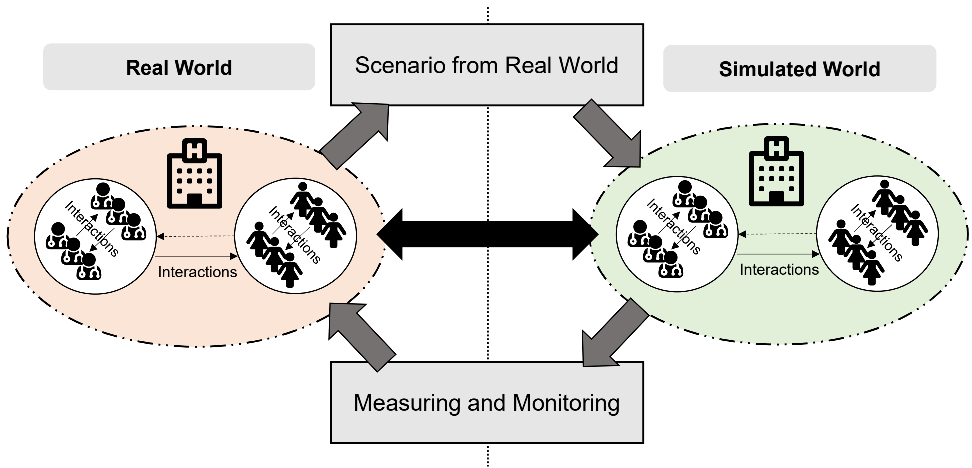


Figure 2.8: Virtual world integrating digital healthcare assets (physical agents), digital workforce (human agents), and digitised business process form the *augmented experimentation* platform

A realistic DSS for business processes, such as a simulation model of a OR-WPS, require near real-life and reliable input data with a reasonable cost of data collection. In the following section (2.2.5.1), the theory of input data is summarised. Thereafter, a specific technique referred to as work-sampling, which is suitable for computer simulation, is be described in section (2.2.5.2).

[46]Source: Antonia Cascales et al. (2013), An experience on natural sciences augmented reality contents for preschoolers [Cas+13]

2.1.5 Value of EA and IM

Enterprises—small, medium, and large—must transform their (legacy) business process to resonate with the current digital revolution. Various *outside-in* and *inside-out* perpetual developments impact organizations. In case of such dynamic *external* environments and *internal* business development, a systematic approach such as EA can be employed to introduce *computer simulation* (and DT)-based DSS in enterprises. *Computer simulations* are essentially an application of information technology to support business processes but with a specific purpose, scope, and utility. In order to manage the introduction of computer simulation in an organization, its implications on the information technology landscape must be considered. The theoretical aspects of both *EA* and *information management* are extensively examined in the literature. In this context, Sections (2.1.5.1) and (2.1.5.2) summarise the effective management of the introduction of new technology in the current landscape.

2.1.5.1 Enterprise Architecture

A *strategic* transformation of an organization should be appropriately managed. The goals, such as increased efficiency and service effectiveness, of implemented changes warrant in-depth research. There are schools of thought concerning the best approach to introducing a change in an organization so as to follow its envisioned roadmap. As digitalization becomes an indispensable part of the transformation journey, both computer simulation and DT can be enabling components to reach the organizational goals. Tamm et al.[47] reported organizational alignment, information availability, resource portfolio optimization, and resource complementarity as the main benefits of adopting EA in an organizational transformation narrative. Therefore, a working definition of EA is as provided in definition (2.8).

Definition 2.8. *Enterprise architecture*

> *"A coherent whole of principles, methods, and models that are used in the design and realisation of the organisational structure an enterprise, business processes, information systems, and infrastructure." [Lan17, p. 26]*

[47] Source: Toomas Tamm et al. (2011), How does enterprise architecture add value to organisations? [TS11]

EA, business architecture in particular, plays a vital role in the design and improvement of new and existing processes, respectively, based on the (new) corporate strategy. The IT architecture plays a predominant role on the horizontal *implementation* layer spanning from business information (data and application) to technology. The focus of this thesis is an implementation based on *business* processes using *data* via an *application*, namely, computer simulation. In order to operationalise EA, one can use the concept known as Information Management (IM), as discussed in the following section (2.1.5.2).

2.1.5.2 Information Management

According to Schmidt[48], IM concerns the models, methods and techniques for information management by describing the considerations on the design, development, and utilization of computerised information and communication systems to solve business problems. A contemporary description of IM according to Krcmar[49,50] is as given in definition (2.9).

Definition 2.9. *Information Management*

> *"Information management (IM) is a sub-area of corporate management that ensures the best possible use of information as a resource for corporate objectives. The significance of IM as the planning, management and control of information, information systems (IS) and information and communications technology (ICT) arises from two perspectives: On the one hand, productivity gains can be achieved through the use of ICT by aligning IM with corporate strategy (align). On the other hand, ICT also allows new business processes to be enabled and designed by the IM, providing the technical innovations (enable)." [Krc15, p. 25]*

As digitalization has become a boardroom agenda, IM has also evolved and repositioned itself to become an overarching concept. It concerns the management of information through IT strategy, governance, process, personnel, controlling, and security,

[48] Source: Günter Schmidt (1996), Informationsmanagement [Sch96]
[49] Source: Helmut Krcmar (2015), Einführung in das Informationsmanagement [Krc15]
[50] Translated from German to English

with its building blocks in the management of information economics, management of information systems (IS), and management of information and communication technology (ICT). Krcmar defines *information systems*[51] as in given definition (2.10).

Definition 2.10. *Information Systems*

> *"Information systems (IS) are socio-technical ('human–machine') systems, which comprise human components (subsystems) and are used to provide information and communication according to economic criteria." [Krc15, p. 23]*

Owing to its significance, the need for information provisioning must be comprehended from the perspective of the board (top-down approach) as well from that of the line employees in the organization (bottom-up approach). It is therefore important to briefly define *information needs* as in (2.11).

Definition 2.11. *Information Needs*

> *"Information needs are generally understood as the type, amount and nature of the information that an individual or group needs to perform a task or a group needs to accomplish a task. The information demand expressed represents a subset of the subjective information demand represents. Along with the objective need, it is the starting point for planning the information supply." [Krc15, p. 31]*

The (aforementioned) individuals or groups usually need the support of information technology applications to transform data into information and, usually through understanding, the information to knowledge—this is also a definition of *business intelligence*. According to Laudon et al.[52], four levels of information systems cater to the needs of four groups in an organization. At the top, an executive needs an *executive information system*. Similarly, a *DSS*, *management information system*, and *transaction processing system* are needed for senior managers, middle managers, and staff/workers, respectively. To further emphasise this aspect, a similar concept

[51] Translated from German to English
[52] Source: Kenneth Laudon et al. (2014), Management information systems - Managing the digital firm [LL14]

known as Business–IT Alignment (BITA) can be referred to. In 1993, Henderson and Venkatraman[53] proposed the *strategic alignment model* (SAM) concept, as depicted in figure (2.9).

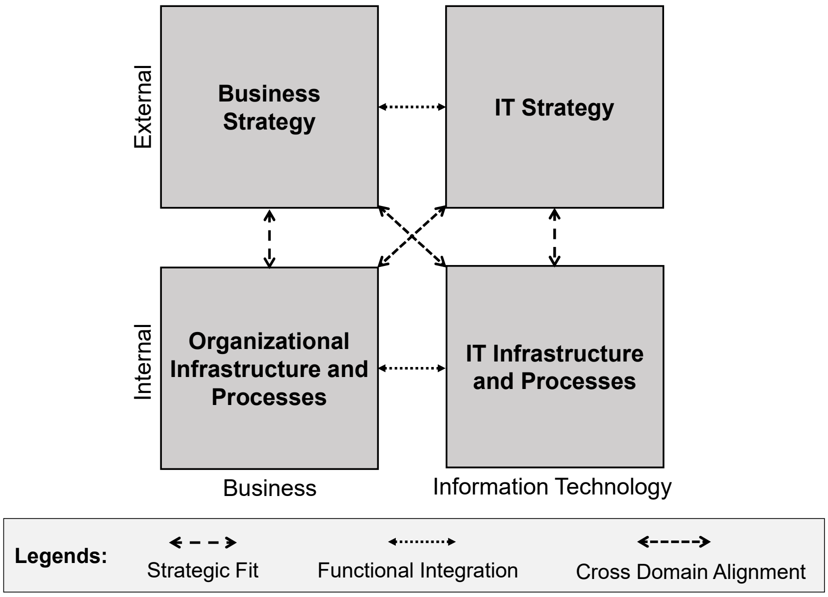


Figure 2.9: Strategic Alignment Model (SAM) by Henderson and Venkatraman

SAM entails a strategic alignment between business and information technology (IT). According to Henderson and Venkatraman, an alignment can be achieved via various paths. However, the business strategy (top-down approach) is usually selected as a starting point and is followed by organizational processes and infrastructure. Henderson and Venkatraman emphasised a need to align the business elements (both external and internal) with information technology (both external and internal) to achieve the objective. An aligned information technology strategy could result in continued, discontinued, or scaled up/down investment in the information technology infrastructure. They further explained the logical path such as starting from "organizational infrastructure and processes" (the bottom left corner) to support an "IT strategy" followed by a "business strategy" to finally achieve the business goals of the healthcare provider at an aggregate level. As regards SAM, Henderson and Venkatraman also provided a thorough examination of the components, namely, business strategy,

[53]Source: J. C. Henderson et al. (1993), Strategic alignment: Leveraging information technology for transforming organizations [HV93]

IT strategy, organizational infrastructure and processes, and IT/IS infrastructure and processes. In the present study, business scope and distinctive competencies are relevant with regard to business strategy. As for IT strategy, technology and systematic competencies form the focus. As regards business, process and skills are the relevant aspects. Regarding IT/IS infrastructure and processes, architecture and skills are of relevance. SAM stipulates coherence among these focus areas to cause positive changes in the organization.

Another model related to BITA is a generic framework for information management proposed by Maes[54], which presents a business–ICT–technology relationship with strategy–structure–operation layers of an enterprise. A modified model of this framework can be the business–information–technology vs direction–implementation–execution layers, as shown in figure (2.10). The focus of the direction layer is as follows: corporate strategy, IT strategy, and technology strategy for business, information, and technology, respectively. In the practical application of this model starting from the *direction* layer, the vision, mission, and objectives for the business unit[55] must be provided by the healthcare corporate strategy.

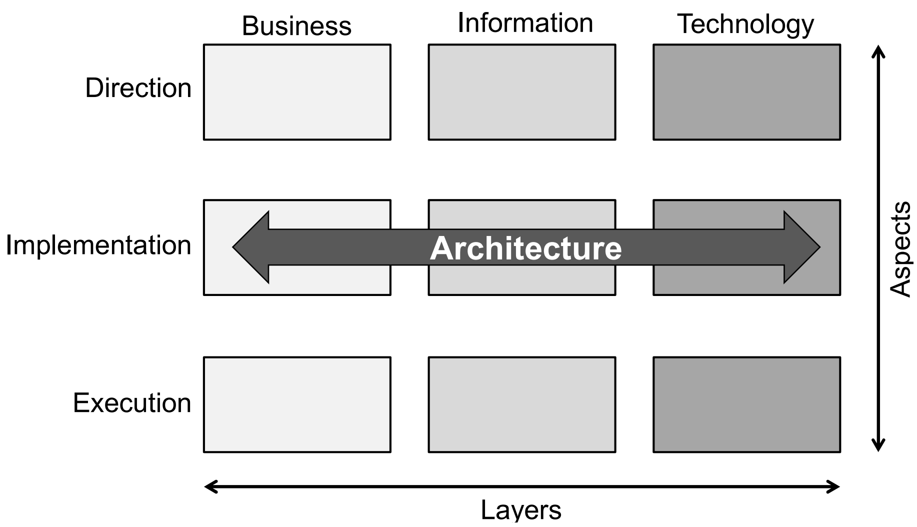


Figure 2.10: Amsterdam Information Model by Maes

As shown in figure (2.10), architecture views are generally created spanning *business-*

[54]Source: Rik Maes (1999), A generic framework for information management [Mae99, p. 8]
[55]In German: Der Fachbereich

process (re)design, documentation, and improvement; they aid in *information-technology* implementation and in achieving digitalization and business objectives of achieving improvements in efficiency and effectiveness. The benefits of employing IM include financial savings, better alignment with the customer information needs, and business-process optimization followed by ever greater value-generation via the use of information systems for the benefit of the business of the organization.

2.2 Work Specific Concepts

Advanced concepts specifically applied or further developed in this work are provided in this section. A brief introduction to the available theory concerning OR-WPS is provided in section (2.2.1). It is followed by an introduction to customers of the business process in section (2.2.2). A brief background of the performance measurement of the process is discussed in section (2.2.3). The advanced concepts to manage the information and architecture in the dynamic enterprise are provided in section (2.2.4). The concluding section (2.2.5) provides the theoretical background of simulation input data followed by work sampling.

2.2.1 OR-WPS Process Area

This study focuses on an enabling process known as OR-WPS. The researcher originally focused on the core processes of enterprises such as hospitals; however, owing to new trends in the shortage of skilled workforce and cost of running ORs, the focus was shifted to enabling processes. Therefore, for clarity, OR-WPS is defined herein—based on field-work in hospitals and the literature—as provided in the following definition (2.12).

Definition 2.12. *OR-WPS*

> *"An OR-WPS is an (enabling) business process with the aim of efficient and effective coordination of skilled groups of staff, who must (actively) participate in one or more medical operations during a workday and deliver value addition to the ORs (core) business process."*

For completeness, two more enabling business processes, namely PTL[56] and CSSD or MS[57], can focus on further research in the future. The CSSD or MS and PTL together with OR-WPS form a network of (enabling) business processes supporting the (core) business process, as shown in figure (2.11). Although the models initially created usually have *chevrons* and *arrows*, the Business Process Model and Notation (BPMN) standard modelled the business process as explained by Sharep et al.[58]. The BPMN is a graphical representation of business processes that are extensively utilised. It is simple and provides a flow-charting notation independent of the implementation environment. In BPMN[59,60] notations, the activities are to be depicted by rounded rectangles, whereas the sequence flows the performance order of the business activities. As described in forthcoming sections, a business process needs to be *transformed* in a state chart[61,62] (or state machine) diagram to develop a multi-agent model for simulation.

The theoretical foundation of this transformation is described by Kufner et al.[63] in their work on BPMN to state-machine diagrams. Another modelling method called UML[64] will be used during *simulation development* is mainly used as another modelling method, while BPMN is valid for at business-analysis. Guizzardi et al.[65] have also concluded that although BPMN is quite suitable for business process modelling, there are *ambiguous* elements, *missing* concepts, and *redundant* elements with regard to simulation; therefore, it is not 100% suitable in the modelling for computer simulation.

56 Note: PTL is an (enabling) business process, which has a scope of communication and coordination for transport of patients from the point of pick-up to the point of delivery and the actual transport.

57 Note: CSSD supports another type of (enabling) business process with a scope of storage, pick-up and provisioning of material needed in the hospital to perform medical operations in the ORs.

58 Source: Alec Sharp et al. (2009), Workflow modeling - Tools for process improvement and applications development[SM 2]

59 In-depth source: Thomas Allweyer (2020) BPMN 2.0 - business process model and notation - Einführung in den Standard für die Geschäftsprozessmodellierung [All20]

60 In-depth source: Layna Fischer (2011), BPMN 2.0 handbook [Fis11]

61 Source: David Harel (1987), Statecharts: A visual formalism for complex systems [Har87]

62 Source: Harel Sobolev (2008), Using the statecharts paradigm for simulation of patient flow in surgical care [Sob+08]

63 Source: Josef Kufner et al. (2019), From a BPMN black box to a Smalldb state machine [KM19]

64 In-depth source: Martina Seidl et al. (2015), UML @ Classroom [Sei+15]

65 Source: Giancarlo Guizzardi et al. (2011), Can BPMN be used for making simulation models? [GW11]

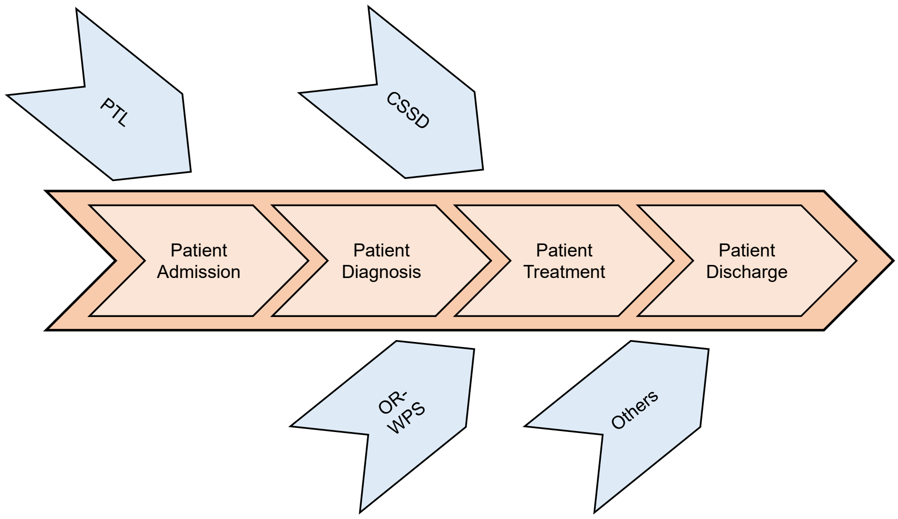


Figure 2.11: Enabling processes such as OR-WPS, PTL, CSSD or MS, and others supporting the core hospital process (based on one of the outcomes of BELOUGA project) from *patient admission* through *patient discharge*, creating value for both patients and the workforce of the hospital

2.2.2 Customer of the OR-WPS

The focus of this work, the OR-WPS as defined in (2.12), involves several actors/agents such as surgeons, medical service workforce primarily from nursing, medical technicians, and anaesthetists; the workforce for ORs are precisely orchestrated by OR schedulers or coordinators. A significant degree of cooperation is required inside and across nursing and other professional groups to provide a trouble-free surgery procedure with high-quality output. The critical success factor (CSF) of the ORs is to have frictionless collaboration and communication. However, this is an ideal situation. Although a detailed theoretical (ideal) process exists, the activities may deviate from the standard in real-world scenarios. Based on a previous research project BELOUGA[66] in figure (2.12), the different roles of the OR-WPS can be described. Every business process has roles that work on activities of the process, and others receive the outcomes of the process; however, the focus is initially on identifying the *value* for the customer of the process.

Customer-perceived value (i.e. the value of the service perceived by the customer)

[66]Source: Stefan Hastreiter et al. (2015), Benchmarking-Studie OP-Personaleinsatzplanung [Has+15, p. 224]

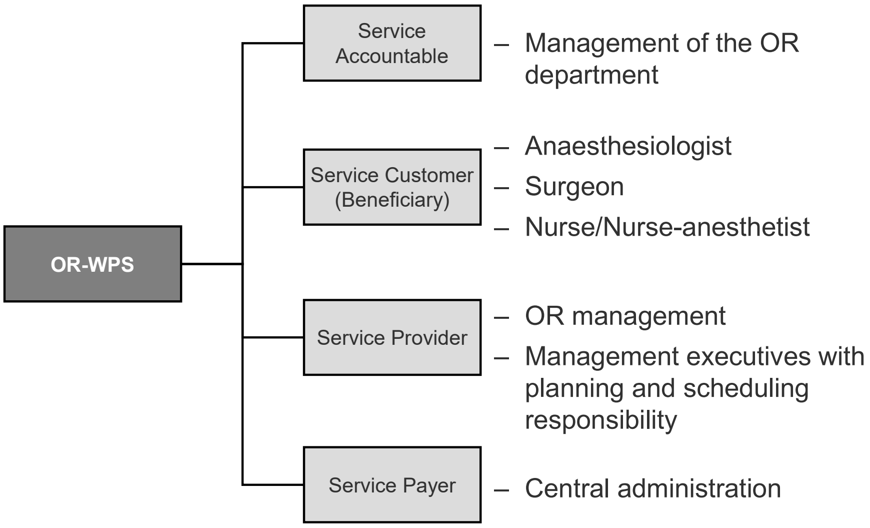


Figure 2.12: Identification of OR-WPS process area's customer, payer, provider and accountability roles (based on one of the outcomes of BELOUGA project)

is used to determine the *value-to-the-customer*. In the aforementioned studies, the service accountable, service customer or recipient, service provider, and service payer were identified. In the proposed simulation model and customer survey, the customers are the focus as the intention is to determine the customer-perceived value and their evaluation and to heuristically calculate customer satisfaction during process operations.

2.2.3 Performance of the Process

This work focuses explicitly on the roles involved to run the OP-WPS business process. They are scheduled by OR coordinators/schedulers of these staff groups. The goal is to measure the (enabling) the performance of the business process in terms of *value-to-the-customer* and then design an integrated dashboard. The performance-related information need of different groups/actors and interests can be managed by posing the following questions:

(a) What is the content of the required measurement information?

(b) How often will the measurement information be required?

(c) In which format should the measurement information be delivered?

(d) How can this acquired information be communicated?

(e) How well can this information address the research questions?

The focus is on the first-three set of questions, which concern content, frequency, and format. This work identified that performance metrics for these questions could be obtained at different hierarchical levels: strategic, tactical, operational, and customer. At the strategic or organizational level, the metrics of interest are from financial perspectives, such as the cost of providing service or the current levels of workforce utilization. The first group at the strategic-management level are actors designated CxO, such as CEO and CFO, whose strategic information needs require a Balanced Scorecard (BSC)[67,68]. The BSC is a method to determine the information needed to evaluate the performance of a company. Its wide application in healthcare is reported in the literature, for example, the work by Voelker et al.[69]. In the context of ORs, at the strategic level, a hospital can measure the following:

(a) total OR utilization;

(b) the revenues from the patient, operating expenses such as staff salaries, contract staff salaries, medical supply expenses, non-medical expenses, institutional expenses, intra-revenue, indirect expenses from supporting departments such as human resources, information technology, marketing, and compliance;

(c) financial indicators such as revenue net to gross, gross patient revenue per volume, supply expenses per volume, and total operating expenses per volume; and

(d) workforce productivity statistics and indicators such as salary paid to the FTEs[70], net-worked FTEs, external agency FTEs, overtime hours as a percentage of salary paid hours, external agency hours as a percentage of net-worked hours, total salary expense per volume, average hourly rate, and net-worked hours per volume.

[67] In-depth source: Robert Kaplan et al. (1996), Using the balanced scorecard as a strategic management system [KN96]

[68] In-depth source: Frank Barthélemy et al. (2011), Balanced Scorecard - Erfolgreiche IT-Auswahl, Einführung und Anwendung: Unternehmen berichten [Bar+11]

[69] Source: Kathleen Voelkder et al. (2001), The balanced scorecard in healthcare organizations - A performance measurement and strategic planning methodology [VRF01]

[70] Note: FTEs mean Full-time equivalents

The most interesting metrics would be learning and growth perspectives at the *tactical* or departmental level. The specialty or departments[71] need OR blocks at the tactical management level to perform surgeries. These can be *in-block*, which usually implies surgeries performed from 7:00 am onwards and scheduled one day in advance; *out-of-block*, which implies those performed from 7:00 am till 11:00 pm and not counted in *in-block*; and *after-hours*, which are the cases performed from 11:00 pm till 7:00 am. Measuring both strategic and tactical levels performance is beyond the scope of this study but mentioned for completeness. The focus of this study is at the *operational level*; the process service cost, quality, and productivity are more relevant. The value component of performance for the process customers can be measured in terms of value dimensions via periodic surveys. In prior research, the factors for the OR-WPS process area were investigated and the mathematical formulae defined and presented by Hastreiter et al.[72]. These factors and final measurements are exhibited in a fish-form as shown in figure (2.13).

Usually, the factors that are measured can be conflicting; for instance, cost optimization can lead to quality degradation. In order to appropriately utilise this measurement, *multiple-criteria decision analysis or making* (MCDA or MCDM) can be utilised[73]. Designing a performance measurement system for the business processes is a well-researched topic and literature from Franceschini et al.[74] and Gladen[75] deep-dived in this theme. By using the factors accompanied by proper measurement, either manually or using computer simulation, one can improve the process or present the results as relevant research findings. Several types of questions, pertaining to research as well as practice, can be answered by the present study. These include the following:

(a) How is the OR-WPS enabling business process performing at the moment?

[71] Examples: acute care surgery, anaesthesia, general, gynaecology, neurosurgery, ophthalmology, dental, orthopaedic, otolaryngology, plastic, psychiatry, surgical oncology, thoracic, urology, and vascular

[72] Source: Stefan Hastreiter et al. (2015), Benchmarking-Studie OP-Personaleinsatzplanung [Has+15, pp. 214-230]

[73] Source: Abbas Mardani et al. (2015), Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014 [Mar+15]

[74] In-depth source: Fiorenzo Franceschini et al. (2019), Designing performance measurement systems [FGM19]

[75] In-depth source: Werner Gladen (2014), Performance measurement [Gla14]

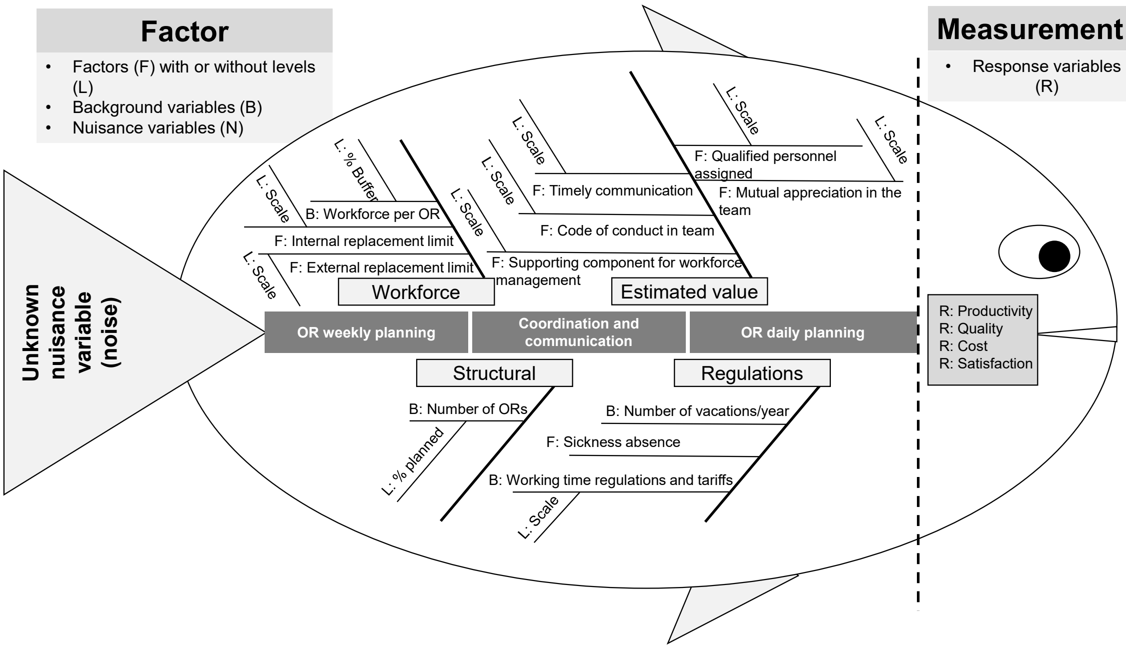


Figure 2.13: Possible performance measurement (based on one of the outcomes of BELOUGA project) in terms of productivity, quality, cost, and customer satisfaction, as well as the underlying factors. Here, the factors can be qualitative or quantitative.

(b) How can the outcomes of OR-WPS be better in the future?

(c) Can a computer simulation be used to measure a *customer-satisfaction*?

Because several factors can potentially be measured, the work employed three classical indicators, namely, productivity (2.2.3.1), quality (2.2.3.2), and cost (2.2.3.3), and one value-based indicator, namely, customer satisfaction (2.2.3.4). These are referred to herein as key performance indicators (KPIs), and they can be quantitative or qualitative[76].

2.2.3.1 Productivity

A definition of *productivity* as in definition (2.13) and detailed descriptions on the ORs productivity in the case of Germany can be found in the work by Berry et al.[77]. The prior study did not entail an analysis on enabling processes such as OR-WPS; this is the focus of this study.

Definition 2.13. *Productivity*

> *"Productivity is simply the relationship between the outputs generated from a system and the inputs provided to create those outputs. Input in the general form of labour (human resources), capital (physical and financial assets), energy, materials, and data are brought into a system. Those resources are transformed into outputs (goods and services)." [Sin85, p. 3]*

Productivity is different from efficiency. The former focuses on the output per unit of input, whereas efficiency focuses on the percentage of input required to deliver an output. Focusing on the productivity of a service such as healthcare, Horbel et al.[78] and Möller et al.[79] have described its theoretical aspects in detail. Based on

[76] Note: In practice, the KPIs should be the variables that could be measured with realistic cost and effort. Measuring the performance of a business Process is a precondition for its continuous improvement. The challenge is to select the appropriate indicators, measure them, and control them for future actions.

[77] Source: Maresi Berry et al. (2008), Operating room management and operating room productivity: the case of Germany [BBSS08]

[78] Source: Chris Horbel et al. (2013), Dienstleistungsproduktivität: Perspektivenwechsel von der Produktions- zur Wertorientierung [HSW13]

[79] In-depth source: Klaus Möller et al. (2014), Produktivität von Dienstleistungen [MS14]

the underlying enabling (supporting) business process, we define the mathematical formulation of the service productivity as in equation (2.1).

$$\textit{Service productivity} = \frac{\textit{Number of surgeries executed}}{\sum_{OG} (\textit{Time taken for daily coordination/creation of OR schedule})} \tag{2.1}$$

where:

OG = Workforce groups such as nurses and anaesthesiologists

2.2.3.2 Quality

Quality concerns the accuracy of the process output. Any improvement activity would consider producing an output at the same or higher level of quality or accuracy with the same or fewer efforts as inputs (cost). As per the Institute of Medicine, *quality* of care in healthcare services is defined as given in (2.14).

Definition 2.14. *Quality of Care*

> *"Quality of care is the degree to which health services for individuals and populations increase the likelihood of desired health outcomes and are consistent with current professional knowledge." [Loh90]*

However, as regards the business process of healthcare services, a description of the *service quality*, as given by Parasuraman et al., is relevant; this is given in definition (2.15).

Definition 2.15. *Service Quality*

> *"Service quality is a measure of how well the service level delivered matches customer expectations. Delivering quality service means conforming to customer expectations on a consistent basis." [PZB85, p. 42]*

A formulation to calculate the quality of the operational OR-WPS process is explained in section (4.2.4.1).

2.2.3.3 Cost

There is always an agreed or better service quality specific *cost* . It is usually a summation of costs incurred because of quality maintenance up some specified standard level and the cost of failure to maintain that standard level. Macario[80] reported on how much it costs the ORs per unit time. For instance, specifically in the case of OR-WPS, it was determined that for the *service quality*, the penalty for displacement/recalling of the workforce for ORs—due to personal reasons such as when someone is ill[81]—may be needed. Nevertheless, the workforce cost may be defined given in definition (2.16).

Definition 2.16. *Workforce Cost*

> *"Labor cost equals the sum of two products: staffed hours multiplied by the cost per hour of staffed hours and hours worked late multiplied by the cost per hour of hours worked late." [MDE06, p. 1504]*

Mathematically, a *service cost* has been defined as in equation (2.2).

$$\boxed{\textit{Service Cost} = \frac{\sum_{OG} \left\{ \textit{(Time taken for daily coordination/creation of OR schedule)} \right\} * CPM}{\sum_{OG} \textit{Planned/scheduled FTE of OGs to be coordinated per day for the OR}}} \tag{2.2}$$

where

$$\begin{aligned} CPM(\mathbf{C}ost\mathbf{P}er\mathbf{M}inute) &= \text{Rate at which each of the OGs cost per minute} \\ FTE &= \text{Full-time equivalent} \\ OG &= \text{Workforce groups such as nursing and anaesthesiologist} \end{aligned}$$

The application of quality definition and mathematical formulation in this work is explained in section (4.2.4.1).

[80] Source: Alex Macario (2010), What does one minute of operating room time cost? [Mac10]

[81] Generally, Germany's absenteeism-based leave information is protected by data-protection regulations and cannot be reported.

2.2.3.4 Customer Satisfaction

Primarily the research and practice have focused on measuring *patient satisfaction* in the healthcare domain; however, *workforce satisfaction* has also been attracting increasing attention. In addition to this, there is a linkage between patient and workforce satisfaction by Janicijevic et al.[82]. However, the question arises as to precisely what customer satisfaction is. It can be defined as in definition (2.17).

Definition 2.17. *Customer Satisfaction*

> *"Customer satisfaction is a measure of how your organization's total product performs in relation to a set of customer requirements." [HA06, p. 2]*

Customer satisfaction measure is one of the lagging but useful indicators for ascertaining the value (leading indicator) of service provision. Satisfaction would be able to show the current state and performance of the service; therefore, it can be a useful indicator for comparisons with the competitors and for evaluating internal customer relationship. Mathematically, customer satisfaction can be represented as follows:

$$\boxed{\textit{Customer satisfaction} = \frac{\textit{Value of offered service}}{\textit{Customer requirements}}} \tag{2.3}$$

A heuristic is developed to calculate the workforce's satisfaction in a computer simulation and is explained in section (4.2.4.2). Other types of performance indicators for business processes exist, for example, the cycle time of the processes, capacity of the process, lead time, process bottleneck, throughput rate, and utilization. Measurement of these indicators is beyond the scope of this work. The implementation of the aforedescribed concepts—namely, the productivity, as detailed in section (2.2.3.1); quality, as described in section (2.2.3.2); cost, as described in section (2.2.3.3); and satisfaction, as detailed in section (2.2.3.4)—is presented in section (4.2.4.1).

2.2.4 Enterprise Information and Architecture Management

In this chapter (2), a brief introduction of the value of applying EA is provided in section (2.1.5.1) followed by a description on the significance of IM in section (2.1.5.2). In the

[82] Source: I. Janicijevic et al. (2013), Healthcare workers satisfaction and patient satisfaction – where is the linkage? [Jan+13]

following sections, an introduction of the most applicable EA frameworks for this work is presented.

2.2.4.1 Enterprise Architecture

Several EA framework and visualization methodologies are available, namely, TOGAF®[83], Sherwood Applied Business Security Architecture (SABSA)[84], DoDAF[85], Nederlandse Overheid Referentie Architectuur (NORA)[86], and Zachman[87]. Matthes[88] provides an extensive overview of different EA frameworks, and a literature review by Zhou et al.[89] affords an overview of several modelling languages for EA. However, ArchiMate®[90] is found to be the most popular for EA modelling. The reference literature for Enterprise-Architecture[91] in ArchiMate® by Karagiannis et al.[92] provides several scenarios for using it for BITA. Therefore, a brief introduction of the Zachman framework is provided in section (2.2.4.2), followed by a description on TOGAF in section (2.2.4.3). TOGAF was used in this study to provide a systematic procedure for developing the architecture of the computer simulation for the OR-WPS process area.

2.2.4.2 Zachman Framework

The complexities of information technology management were demonstrated in the 1980s in a framework for information systems architecture by Zachman[93]. His widely cited six-by-six matrix, with layers of technology management down one side and different business perspectives across the top, was nevertheless not preferred by many managers and architects. Handling 36 different places of interest (the intersection of

[83] Source: https://www.opengroup.org/togaf
[84] Source: https://sabsa.org/
[85] Source: https://dodcio.defense.gov/Library/DoD-Architecture-Framework/
[86] Note: A reference framework from the Dutch Government and regulatory framework.
[87] Source: https://zachman.com/about-the-zachman-framework
[88] Source: Dirk Matthes (2011), Enterprise architecture frameworks kompendium [Mat11, p. 38]
[89] Source: Z. Zhou et al. (2020), A systematic literature review on enterprise architecture visualization methodologies [Zho+20]
[90] Source: https://www.opengroup.org/archimate-forum/archimate-overview
[91] In German: Unternehmensarchitekturen
[92] Source: Dimitris Karagiannis et al. (2020), Benutzerzentrierte Unternehmensarchitekturen [KMH20]
[93] Source: J. A. Zachman (1987), A framework for information systems architecture [Zac87]

the matrix's six rows and six columns) was deemed challenging. Nevertheless, from a researcher's perspective, the framework is remarkable, as it affords a new approach on the field of architecture and its practical application.

2.2.4.3 TOGAF® Framework

TOGAF® is a methodology with principles, tools, and practices for guiding processes toward a specific purpose. Suppose a DSS based on a computer simulation using ABMS or MAS technology is to be introduced in healthcare service. Then, it is essentially a transformation of the information technology landscape of the ORs. A methodology such as TOGAF®[94] can support this change. An overall architecture based on TOGAF® intends to provide a control. In this study, the key stakeholders and their concerns were considered, and the architecture principles, models, and views for computer simulation of business processes in the research scope were developed. In order to appropriately scope the phases relevant to this study, only the essential phases of the Architecture Development Method (ADM)[95], as shown in figure (2.14), were employed. In the scholarly literature search conducted in October 2020 on Google Scholar[96], few studies were found that employed TOGAF® to manage the implication of using computer simulation on the future information technology landscape. For instance, Rijo et al.[97] described a proof-of-concept (PoC) development based on EA to help address the information needs of hospitals. The TOGAF® phases used were as shown in figure (2.14). A short description of these phases are provided in table (2.2).

In summary, the EA development process has the following aspects: preliminary[98], architecture vision, and architecture change management as strategy and motivation layer; business architecture as business layer; information systems architecture (data and application) as application layer; technology architecture as technology layer; and opportunities and solutions, migration planning, and implementation governance as

[94] Source: TOGAF® Standard, Version number 9.2

[95] Note: ADM is copyright of the Open Group and used with their permission.

[96] Source: https://scholar.google.com/

[97] Source: Rui Rijo et al. (2015), Developing an enterprise architecture proof of concept in a Portuguese hospital[RME15]

[98] Note: Preliminary, implementation governance, and architecture change management are out of the scope of this work.

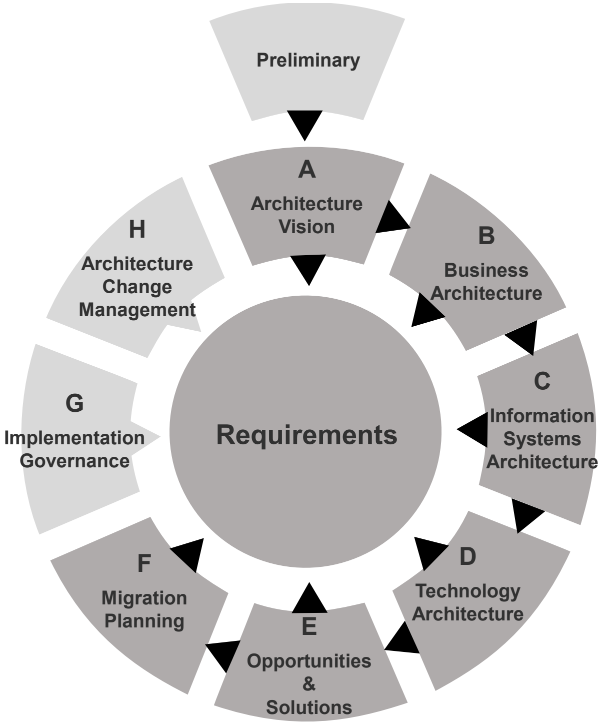


Figure 2.14: Architecture Development Method (ADM) cycle in which only phase circles in dark grey are in scope and light grey are out of scope of this work

Phase	Brief description
Requirements Management	The business requirement is identified, collected, validated, stored, prioritised, and available to relevant phases of the Architecture Development Method (ADM) cycle
A - Architecture Vision	Setting the scope, constraints and expectations, stakeholder identification, expectation management and relevant corporate & regulatory approvals
B - Business Architecture	Develop architecture for concern of the Business
C - Information Systems Architectures	Develop architecture for concerns of both Application and Data domains
D - Technology Architecture	Concerns and opportunities in the Technology domain
Opportunities and Solutions	Initial implementation planning through the conceptual roadmap and, if needed, a transition architecture
Migration Planning	Although the phase is called Migration Planning, only implementation plan to reach the Target architecture

Table 2.2: Description of phases of TOGAF® used in this work. For phases B-C-D, both Baseline and Target architectures could be developed

parts of implementation and migration layer. From an EA perspective, having control of the *changes* caused by the different transformation projects is crucial. A simulation technique can evaluate the changes that are intended to introduce a positive transformation of the business process. Specifically, a quantitative simulation can be employed to determine measured values of the performance indicators of a business process in question and provide confidence to the management before the implementation of the changes in the actual business process. A few questions that this study will potentially help address are as follows:

(a) What would be the implication of the simulation results on the actual business process changes?

(b) What about any other process scenario that is not examined in the simulation but could be more promising?

(c) Which criteria and their combination could be used to get more favourable changes in the actual business process?

This study employed EA to provide a structure to propose future changes on the basis of computer simulation. An aligned transformation in the various layers, such as organization, processes, IT applications, and infrastructure technologies, is a critical factor for success of current healthcare service providers. During a transformation, any methodology, including a computer simulation, may be used. The major challenge is in managing the sum of several change initiatives in an enterprise, resulting in either positive, negative, or neutral overall gains. The purpose of using EA is to align the healthcare enterprise to its fundamental obligation and business requirement.

The external regulation and compliance force the healthcare services to provide attractive offers and simultaneously lower costs in the value chain, value network, or value shop[99]. In the present service-oriented economy, the customers expect such offers, and enterprises such as hospitals should design the business process with the best possible alignment with their current (i.e. baseline) and future (i.e. target)

[99] Source: Charles Stabell et al. (1998), Configuring value for competitive advantage: on chains, shops, and networks [SF98]

IT landscapes[100]. In order to be effective, a limited choice on the relevant architectural principles has to be made, as suggested by Greefhorst et al.[101]. It would be reasonable to guide the future business process and IT system design decisions. Many architectural viewpoints were considered in order to model the research problem in this study, as presented in the following sections. In order to articulate them in a standard language, ArchiMate® 3.0 can be used as suggested by Jonkers et al.[102]. These viewpoints address the various stakeholder concerns, organizational and process understanding, information needs, state-of-the-art technology following an outside-in approach, and how the research problem is addressed.

2.2.5 Simulation Input Data

Some background information concerning the simulation is provided in section (2.1.3), followed by the design of the experiment in section (2.1.4). Several prior studies are available concerning simulation in general, ABMS[103] and MAS[104] in particular. Therefore, the details are not included herein. In sections (2.2.5.1) and (2.2.5.2), detailed theoretical descriptions concerning the simulation input data modelling and work sampling are provided, respectively.

2.2.5.1 Input Data Modelling

Without accurate data, simulation models cannot be used in production environments in hospital as a DSS. The simulation models using both DES and ABMS or MAS by design have stochastic elements, which imitates the probabilistic nature of real-system inputs. As shown in figure (2.15) and adapted based on Gadatsch[105], there are two variables for a process simulation—*process-oriented* or *resource-oriented*. Based on the goal of simulation in this work and the possibility of gathering appropri-

[100] Source: J. C. Henderson et al. (1993), Strategic alignment: Leveraging information technology for transforming organizations [HV93]

[101] Source: Danny Greefhorst et al. (2011), Architecture principles - the cornerstone of enterprise architecture [GP11]

[102] Source: Henk Jonkers et al. (2017), How to use the TOGAF® 9.1 architecture content framework with the ArchiMate® 3.0.1 modeling language [Jon+17]

[103] Source: Franziska Klügl (2009), Agent-based simulation engineering [Klü09]

[104] Source: Stefan Kirn et al. (2006) , Multiagent engineering [Kir+06]

[105] Source: Andreas Gadatsch (2013), Grundkurs Geschäftsprozess-Management [Gad13a, p. 101]

ate data, both *time-oriented* and *mass-oriented* inputs from process and resources, respectively, are plausible. One can focus on collecting statistically-based data on activity times in a time-oriented magnitude. During the simulation operation, one can provide many resources to perform the activities. These input-type sources are to be identified, the value ascertained, and collected during the job-shadowing-phases in respective hospitals, while upholding the data protection and scientific regulations.

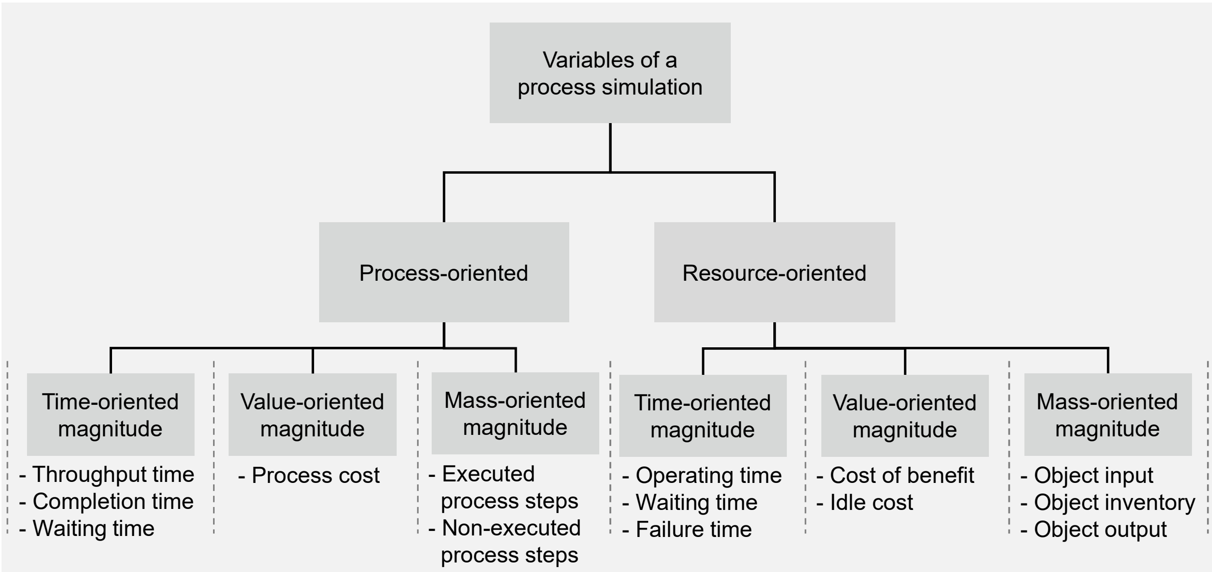


Figure 2.15: Computer simulation experiment variable types

Leemis[106] has described *input modelling taxonomy* in the form of a tree diagram, which features time-dependent and stochastic models. Based on its suitability for the problem at hand, the logical starting point was to use a *time-dependent* univariate continuous model, a *normal distribution*[107]. In order to follow a systematic procedure, this work entailed consulting the procedure recommended by Law[108]; however, the challenge lies in the method of data collection. It is impractical to measure times of OR-WPS activities performed by the OR scheduler in real-time without IoT[109]. *Work sampling* is a suitable procedure to determine the normal distribution of time taken by

[106]Source: Lawrence Leemis (2001), Input modeling techniques for discrete-event simulations [Lee01]
[107]In-depth source: Manuel Laguna et al. (2013), Business process modeling, simulation, and design [LM13, p. 512]
[108]Source: Averill Law (2011), How to select simulation input probability distributions [Law]
[109]Note: The use of tracking devices was not in the scope of this research work.

different process activities of the OR scheduler in a probabilistic setting, as explained in the following section (2.2.5.2).

2.2.5.2 Work Sampling

The *working time* determination/measurement methods can be classified as *experimental* method or *computational* method, as shown in figure (2.16). The experimental methods can be either external recorded or self-recorded[110]. The external (recorded/written) methods are manual, with the help of statistics or in an interview. The manual recording can be performed using a stopwatch or using the REFA[111] procedure as mentioned by Schlick et al.[112]. Time measurement can also be performed using statistical methods such as *multi-moment frequency method* and *work sampling*[113] and provide statistical time models as an outcome. Another set of computational time measurement methods exists but is not considered in this work[114]. Originally from the Industrial Engineering domain, *work sampling*[115] is a competent mechanism to investigate the distribution of people's activities while performing a business process, whether in a function or across functions. A definition of work sampling, as provided by Aft, is as follows:

Definition 2.18. *Work Sampling*

> *"Work sampling, or activity analysis, is the process of making sufficient random observations of an operator's activities to determine the relative amount of time the operator spends on the various activities associated with the job." [Aft00, p. 300]*

[110]Note: The self-time determination/measurement methods such as a person with a list of activities with duration and frequency and frequency of occurrences using work equipment or employing computational devices is out of scope in this work.

[111]In German: Reichsausschuß für Arbeitszeitermittlung

[112]Source: Christopher Schlick et al. (2018), Arbeitswissenschaft [SBL18]

[113]In German: Multimoment Häufigkeitsverfahren (MMH)

[114]Note: They are either by comparing and estimating with similar type of work or through a combination of systems of predetermined times such as methods-time measurement (MTM), work factor (WF), planned times, nomogram, or by calculating of activity times according to business process models, geometric computer-aided design (CAD) models, and quantitative information models. Ultimately, they provide sequential-analytic time models.

[115]In German: Multimoment (MM) Verfahren

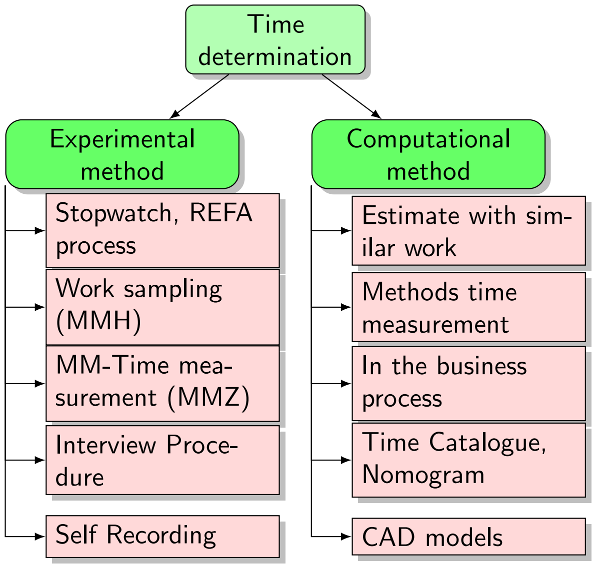


Figure 2.16: Overview of the methods of time measurement in a typical industrial workplace

Alternative methods such as time-study could not be employed as standard (predetermined) data on the OR-WPS workforce scheduler was unavailable. Compared with an assembly-line for mass-production of physical articles, which have relatively low to short-cycle times and are repeated many times during a working day, almost all the activities in the OR-WPS process area are long cycle times and fast repetition rates. Hence, a reasonable estimate would require observation of very long duration (in terms of days or months). It is costly and out of the scope of this study. The scope is to make a sufficient number of random observations of the “OR scheduler" for nurse and nurse–anaesthetist and determine the relative amount of time they spend on various daily activities in the ORs. A link to the historical activity time is not within research scope, whereas *sufficient* observations could be collected in a “specific" time frame.

Specifically, in the multi-moment work-sampling study as a sampling method, the estimates of the relative frequency or duration of predominantly irregularly occurring work activities or variables of a similar nature are used with a measurement accuracy of choice and statistically significance value (α). Compared to the multi-moment time-measurement method[116] that delivers measurements in minutes and hours, the

[116] In German: Multimoment-Zeitmessverfahren (MMZ)

multi-moment frequency method (MMH) delivers absolute frequency and percentage values. In terms of statistics, a multi-moment work-sampling study is a process of collecting a large sample (of activity) from the population (of activity) with samples collected without bias and the observed entities not interfered. The activities are observed and noted during a job-shadowing as being events form a sample in the statistical sense. Using statistics, one can infer based on the sample for the same sample population. The samples must be taken from random observations with a notation of the instantaneous occurrence of an activity. The focus is also on collecting a sufficient number of sample observations. The irregularity or randomness of the observation gives each possible activity of an event an equal chance of being observed and recorded. The work sampling technique has been used in healthcare services to analyse nursing staff productivity[117] or the nursing staff time allocation in long-term care[118] with a goal of optimised scheduling. The detailed application of this technique in this study is explained in section (5.4).

2.3 Related Work

The following sections (2.3.1), (2.3.2), and (2.3.3) juxtapose “creating a multi-agent simulation for OR-WPS" with “research findings" by other authors who have investigated similar situations. The focus is on the resemblances and differentiation, business process, research method, the findings, and simulation approach to answering the research questions.

2.3.1 Semi-Systematic Literature Review

A comprehensive literature review on ORs planning and scheduling by Cardoen et al.[119] have focused on review on operations research and revealed that most of the research was directed on planning and scheduling of elective patients (the receiver of healthcare service) but not on the workforce (the providers of the service). Compared

117 Source: B. K. Hagerty et al. (1985), Work sampling - Analysing nursing staff productivity [HCS85]
118 Source: Providencia Cardona et al. (1997), Nursing staff time allocation in long-term care - A work sampling study [Car+97]
119 Source: Brecht Cardoen et al. (2010), Operating room planning and scheduling - A literature review [CDB10]

to evidence-based medicine, which extensively uses these reviews, a procedure for applying SLR in *Software Engineering* was reported by Kitchenham et al.[120] and was followed in this work. The desire for a review was required due to the unavailability of one at the time of study combining process improvement via multi-agent simulation in the healthcare service domain. Except for an article subsequently published by Isern et al.[121] with an overall focus on healthcare, none was found that provided a specific, thorough, and unbiased review.

Van Lent et al.[122] have focused on reviewing improvements in a hospital and computer simulation. They have provided a few recommendations that include alignment with the client's objectives, business benefits, acceptance of the results and their execution, and detailed technical quality factors for a successful simulation implementation. Notably, a previous study by Brailsford et al.[123] has identified challenges, especially in *stakeholder management* during or after simulation model for practical use in National Health Service (NHS) in the United Kingdom (UK). They proposed a list of ten factors for successfully implementing a simulation project. These factors concern stakeholder engagement from inception till go-live, paying attention to data quality and suitable simulation tooling, more extensive use of the tool where possible, and allocating commensurate resources. These findings validate the proposed use of EA right from a Proof of Concept (PoC) simulation initiative for better alignment between the medical departments and information technology (IT) as proposed herein.

Jun et al.[124] have provided an extensive literature review on the application of DES in healthcare clinics. They concluded that extensive research was conducted in the area of patient flow as well as resource allocation. Furthermore, the simulation is beneficial owing to multiple performance measures. Notably, a comprehensive, integrated multi-facility systems simulation is lacking; this is the visionary idea behind a

[120] Source: B. Kitchenham (2007), Guidelines for performing systematic literature reviews in software engineering [KC07]

[121] Source: David Isern et al. (2010), Agents applied in health care: A review [ISM10]

[122] Source: Wineke AM van Lent et al. (2012), A review on the relation between simulation and improvement in hospitals [vVv12]

[123] Source: Sally C. Brailsford et al. (2009), Stakeholder engagement in health care simulation [Bra+09]

[124] Source: J. B. Jun et al. (1999), Application of discrete-event simulation in health care clinics: A survey [JJS99]

DT of the future healthcare service providers such as hospitals. Khemakhem et al.[125] have reviewed the published research based on theoretical, technical, agent and application views. The following section (2.3.2), presents the related work concerning multi-agent simulation and modelling.

2.3.2 Multi-agent Simulation and Modelling

In his articles and primers regarding "Computer Simulation and the Philosophy of Science," Winsberg[126] has presented an in-depth case of using computer simulation as the third pillar of scientific investigation along with theory and experiment. Barnes et al.[127] have published value-proposition of computer simulation as a valid scientific method that allows significant exploration of multiple options without enormous capital expenditure in terms of budget and resources with an added advantage of experimentation in a safe virtual environment. Cardoen[128] has thoroughly researched the OR planning and scheduling on the detailed timetable showing at what time or date activities, that is, surgeries could start and end following a mathematically optimised scheduling. Investigations in this regard have also been based on *mixed-integer linear programming* and the *dedicated branch-and-bound approach*. The present study contrasts with that of Cardoen in that a multi-agent simulation model was employed in this study to measure the classical and value-based indicators of a high-level daily schedule. A literature review of the simulation using mathematical programming, such as discrete-event, Monte Carlo, and heuristic approaches for OR planning and scheduling in hospitals was summarised by Cardoen et al.[129].

The application of *agents* in healthcare was reviewed by Isern et al.[130]. They have investigated the emergence of an agent-based viable approach for developing autonomous systems in the healthcare domain. It could review articles published be-

[125] Source: Faten Khemakhem et al. (2020), Agent-based intelligent decision support systems: a systematic review [Khe+20]

[126] Source: Eric Winsberg (2009), Computer simulation and the philosophy of science [Win09]

[127] Source: Barnes et al. (1997), Success stories in simulation in health care [Bar+97]

[128] Source: Brecht Cardoen (2010), Operating room planning and scheduling: solving a surgical case sequencing problem [Car10]

[129] Source: Brecht Cardeon et al. (2010), Operating room planning and scheduling: a literature review [CDB10]

[130] Source: David Isern et al. (2010), Agents applied in health care: A review [ISM10]

tween the years 2002–2008. They concluded that the agent-based systems afforded value addition by being *reusable, reliable, flexible, robust, maintainable,* and *adaptable*. Many of the agent-based contributions were PoCs but could integrate the legacy systems. Gath[131] examined the applicability of the *dispAgent* multi-agent system in the complex logistics transport process domain by identifying, configuring, and extending the system to fulfil an industrial partner's requirements. Gath also validated real-world data from the industrial partner. The developed multi-agent system outperformed the standard software. In the case of the proposed ServiceSim OR-WPS in this study, the performance was not the issue, as the time taken to compute the results was on the order of seconds. Therefore, a computational time study was not needed in ServiceSim, and its simulation time was acceptable. Kuehn[132] reported on a scenario-based simulation experiment in a community health centre[133]. They researched on essential practical knowledge for outpatient and networked patient care planning, modelling, and implementation based on a new classification of structured treatment procedures according to care categories by using a simulation program. Several scenarios of scheduling physicians as well as nursing staff and duration of their work-day were considered; it was found that the number of workers influences the length of the working day. One additional worker could reduce the daily working time for the treatment of all 132 patients by 4 h.

Similarly, Centeno et al.[134] used a simulation-ILP based tool for scheduling emergency staff. Ismail et al.[135] integrated a balanced scorecard and simulation modelling for emergency department performance management. Another literature by Abo-Hamad et al.[136] proposed integrating simulation at strategic decision support rather than only applied in tactical and operational ones and came up with a multi-criteria

[131] Source: Max Gath (2016), Optimizing transport logistics processes with multi-agent planning and control [Gat16]

[132] Source: Klaus Kuehn (2010), Simulation von Behandlungspfaden mittels VAO-Technik [Hel10, p. 231]

[133] In German: Medizinisches Versorgungszentrum (MVZ)

[134] Source: M. A. Centeno et al. (2003), A simulation-ILP based tool for scheduling ER staff [Cen+03]

[135] Source: Khaled Ismail et al. (2010), Integrating balanced scorecard and simulation modeling to improve emergency department performance in Irish hospitals [IAHA]

[136] Source: Waleed Abo-Hamad et al. (2013), Multi-criteria approach using simulation-based balanced scorecard for supporting decisions in health-care facilities: an emergency department case study [AHA13]

approach for a balanced scorecard. Simulation can be helpful in natural disaster relief, as described by Cao et al.[137], given the potential scarcity of human resources. This situation is experienced in the ongoing Coronavirus Disease 2019 (COVID-19) pandemic in 2020 and 2021. It provides an impetus to adopt digitalization, artificial intelligence, and computer simulation to support decision-making during healthcare provision crises in the future.

The proposed ServiceSim OR-WPS should provide a robust, flexible, reactive and proactive multi-agent system that can model real-world agents such as nurses and facilitate the agent to coordinate, communicate and negotiate according to the defined OR-WPS enabling business process. Proposed multi-agent systems, such as ServiceSim OR-WPS, should be *decentralised by design* and *interoperable*; this implies that the agents modelled in OR-WPS can be reused and, with low effort, internally customised and applied in a new real-world situation to simulate. The model should be receptive to (real-world) sensor data IoT input and create scenarios supporting OR coordinator decision-making for workforce scheduling[138]. The following section (2.3.3), focuses on related works on qualitative and quantitative data analysis concerning the area of interest of this study.

2.3.3 Quantitative & Qualitative Data Analysis

Underlining the economic significance of information, Levitan[139] conceptualised a life cycle of information production, from generation to institutionalization, maintenance, and dissemination. Subsequently, the model developed by Levitan was studied by Rehaeuser et al.[140], who reported that the structural factors of the corporation and institution under consideration and the use of information technology can influence *knowledge* generation. Similar to work-sampling, to control high-costs of operating

[137] Source: Hui Cao et al. (2012), Principles of scarce medical resource allocation in natural disaster relief: a simulation approach [CH12]

[138] Note: Further relevant studies that cover simulation modelling and its application in the healthcare service domain are not described herein owing to space constraints. Instead, their titles are mentioned in the list of Semi-SLR.

[139] Source: Karen Levitan (1982), Information resources as "Goods" in the life cycle of information production [Lev82]

[140] Source: J. Rehaeuser et al. (1996), Wissensmanagement im Unternehmen [RK96]

ORs, Weinbroum et al.[141] have focused on measuring utilization time in a hospital in Israel. They also related the time-waster with the cause behind it for the ORs. Their statistics in terms of sample size median is helpful for the ORs in other hospitals subjected to similar environmental conditions. In a study by Joustra et al.[142], they reported that the *statistical-models* can provide better estimates than surgeons. Work-sampling results from this work could provide estimates in terms of *normal-distribution* for OR-WPS stakeholders. They can guide the hospital OR management to accommodate these in-house or off-the-shelf OR scheduling algorithms for better planning.

In 2007, Marjamaa et al.[143] surveyed chief-anaesthesiologists and head-nurses of 103 surgery units belonging to 60 public hospitals. They focused on the concurrent structures of daily operations management, metrics, and tools used to monitor the operating room's performance. They found that the surveyed staff mentioned "collaboration and communication between the care providers" as an essential value dimension. The findings in the survey conducted in this study both in German hospitals and an American hospital in Missouri agree with this survey conducted in Finland in a similar operating rooms environment. Similar to the (qualitative) content-analysis performed in this work, a similar study published by Bogdanovic et al.[144] focused on team performance in the ORs subjected to coordination behaviours and adaptive coordination strategies employed by surgical teams. They conducted a qualitative content analysis of semi-structured interviews of several workforce members covering different departments and hospitals and revealed the importance of non-technical skills that support (safe) performance in the surgical teams. As compared to this study, Bogdanovic et al. have adopted rigorous methodology to arrive at their research conclusions.

In summary, this study aimed to demonstrate a relationship among *data*, *information*, and *knowledge* via different approaches. The results of the *work-sampling*

[141] Source: Avi Weinbroum et al. (2003), Efficiency of the operating room suite [WEE03]

[142] Source: Paul Joustra et al. (2013), Can statisticians beat surgeons at the planning of operations? [JMv13]

[143] Source: R. A. Marjamaa et al. (2007), Who is responsible for operating room management and how do we measure how well we do it? [MK07]

[144] Source: Jasmina Bogdanovic et al. (2015), Adaptive coordination in surgical teams: an interview study [Bog+15]

approach are presented in section (5.4). The results from international *survey* are detailed in section (5.5), and those from *content-analysis* are presented in section (5.6).

3 Problem Description and Problem Statement

Abstract: *This chapter presents a specific problem unambiguously faced by healthcare service providers such as hospitals. The main focus is on introducing the OR-WPS process at a high level with relevant details. The justification as to why detailed research on OR-WPS is essential, the motivation behind the research, observations from American and German hospitals along with the notable differences, and how the process works at a high level of abstraction are summarised. Assumptions and constraints relevant to this study are also provided where appropriate.*

3.1 OR-WPS at a German Hospital

In this work[1], a high-level patient flow for surgery in the ORs is expressed, as shown in figure (3.1). This high-level process was developed on the basis of subject matter expert interviews, observations, and documentation received from a hospital[2]. The patient flow begins with transporting a patient from the ward to the anaesthesia, then to an OR, post-anaesthesia care, and back to the ward. Several coordinators belonging to several occupational groups, such as those at the ward and transport department are involved. The following sections explain relevant details of an OR-WPS process area[3].

[1] A part of the work was conducted as part of the BELOUGA project.

[2] Note: The name of the hospital cannot be disclosed to preserve anonymity.

[3] Note: The inpatient and any other medical treatment related to ORs are out of scope of this work. A detailed analysis of the patient flow at the ward, anaesthesia ward, and post-anaesthesia ward, as well as patient transport logistics, are out of the scope of this work but summarised for completeness. Any bottlenecks due to these out-of-scope processes are not considered herein.

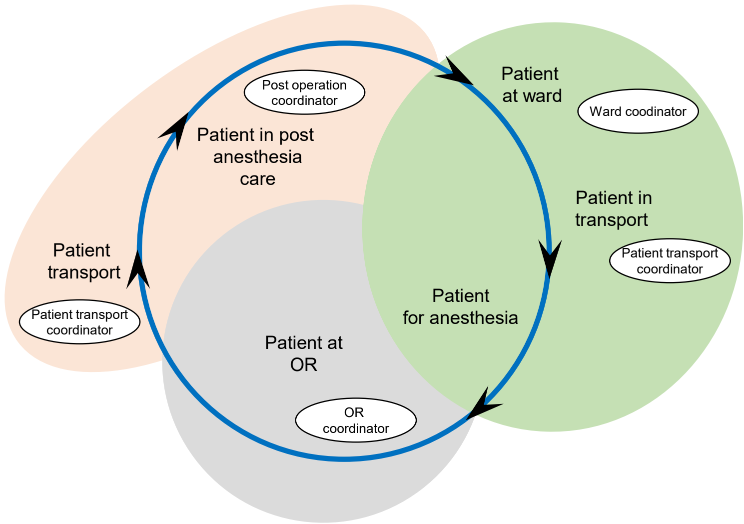


Figure 3.1: Observed patient flow during the surgery in an operating room

3.1.1 Pre-operative Phase

A part of an End-to-End (E2E) of the OR-WPS process is illustrated in figure (3.2). A senior surgeon with several years of experience is generally in-charge of ORs planning and follows a well-defined protocol[4]. Process activities that run in parallel are displayed adjacent to each other, and their outcomes are inputs to other processes. All senior surgeons representing their medical department must enter the scheduling and OR occupancy of the patients to be operated in an Information Technology (IT) application a day before the surgery. Every day around 7:30, all emergency changes made in OR occupancy plan the day before are assessed, and a new plan is approved. While performing the PTL process[5], the ward coordinator, PTL coordinator, and OR coordinator move the patient from the patient ward to their respective anaesthesia area before moving to an OR. The surgical procedure is once again discussed among (senior) surgeons and residents at the 7:45 review meeting, with a daily goal to successfully start the operations at 8:00. The ward staff is not actively involved in the OR planning process but follows the OR coordinator's orders to send the patients. The SAP enterprise resource planning (ERP) system, which is employed for

[4]Note: A few medical processes run parallel to the OR-WPS process; however, they are not the focus of this work.

[5]Source: Franziska Jehle et al. (2015), Benchmarking-Studie Patiententransportlogistik (PTL) [Jeh+15]

OR planning, is accessible from all computers in the hospital. The patient ward has only read-access to the OR daily plan. It also has information concerning the execution of the plan, which is also known as the OR run-log. The progress of a particular surgical operation can be estimated on the basis of the information from the ORs.

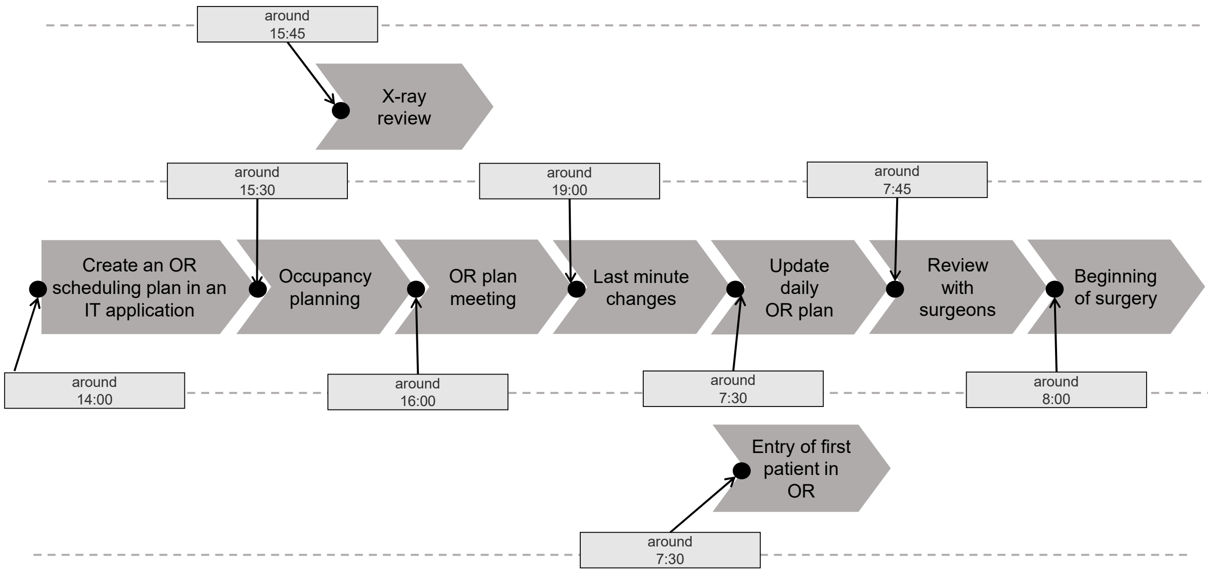


Figure 3.2: Observed high-level OR-WPS process a day before reopening ORs without adhering to any standard modelling convention

3.1.2 Post-operative Phase

Upon the completion of the surgery, depending on its type and potential complications, the patient is transported following the PTL process to a post-surgery anaesthesia care area until the patient is fully conscious, as shown in figure (3.1). The patient is then transferred to the respective ward for post-surgery care followed by a rehabilitation program elsewhere.

3.2 OR-WPS at an American Hospital

For comparison with the OR-WPS process at the German hospital, a similar observation was performed at the University of Missouri Health Care (UMHC). Hospitals in the

United States can be classified into three main types, namely, academic; community-based and university-affiliated; and community-based but without affiliation to any academic institution. The University of Missouri at Columbia, USA, operates several academic hospitals and around 37 clinics in Missouri, with the central hub at Columbia and Kansas City, MO. Because of its academic nature, the medical workforce of the hospital consists of both trained surgeons and nurses as well resident and trainee nurses. At a high level of abstraction, an American hospital in Missouri had similarities to the business process observed in the German hospital as described in section (3.1). However, they presented significant differences in terms of method of organising roles and services. In this section, both the similarities and differences are described based on interviews conducted at the University of Missouri Health System (UMHS) hospital in the Missouri state of USA.

3.2.1 Specific Roles

At UMHS, the surgeons and physicians have a contract with the hospital. In contrast with the German system, they practice in the healthcare providers' premises as a third party. The remuneration of surgeons and physicians is based on negotiated rates with the hospital before commencing their services. First, the surgeons and physicians have greater autonomy to decide on when and how often they will provide their service and how much quota of daily, weekly, or yearly services they would prefer to provide. Hospital administration has less authority over this issue but profits from the performance of their services. The surgeons and physicians typically prefer to *block schedules* and provide their services in terms of *service time*. Further, there is another category of surgeons and physicians whom the medical departments at UMHS directly employ. Their responsibilities include practising medicine and teaching medical students. Owing to such an allocation, there exists an ORs resource conflict for surgery blocks among the departments. The *relative importance*, *historical utilization*, and *influence* play a significant role in the allocation of surgery blocks to the departmental surgeons. The surgeons in each department negotiate for their share within the departmental OR. There is also a *penalty system* in place for scenarios wherein the allocated OR time is not fully utilised, thereby impacting future allocations.

This category of physicians provide their service in a geographical region in the US;

in Europe, they are known as general practitioners. The family physician performs surgeries at the healthcare provider's premises and can therefore ask for ORs slots. They can be potential reasons for last-minute changes in the ORs schedule if the severity of their patient's condition requires immediate attention followed by surgery. Hospitals accept the services of locum surgeons as well. They need to step in when a surgeon scheduled for an operation is unavailable because of sickness or other unavoidable circumstances. *Locum* surgeons have agreements with the hospital to fulfil their services. *Residents*, who also practice medicine, have to perform patient treatment under direct supervision for at least three years. Their working contract is different from that of a physician who already went through residency, and they can have rotational shifts to different wards for at least a year. In the German medical education system, the residents are referred to as *trainee doctors*[6]. Aside from the surgeons and physicians, another group of staff who are vital to running an OR is the *nursing* workforce. Hospitals usually employ a full-time *registered nurse*. A *PRN nurse*[7] is a nurse not employed by the hospital but can fulfil the staffing as per need basis. They are helpful in case of natural calamities, emergencies, and if the registered nurse falls ill. Contrary to the German system, an experienced nurse acted as an *OR coordinator or scheduler*, responsible for planning and scheduling nursing staff for the ORs. Apart from the categories, there exist other roles, namely, *nurse anaesthetist* (CRNA), *nurse practitioner* (NP) and *licensed practical nurse* (LPN).

3.2.2 Specific OR Structure

A *super-system map* to depict the UMHS was developed, as shown in figure (3.3). The UMHS is divided into the University Hospital (UH), MOI, and Women's and Children's hospital. The study was conducted at the UH. At the UH, there are a total of 16 ORs (including one for trauma), which are designated as follows: 6, 7, 8, 10, 11 (trauma OR), 12, 14, 15, 16, 17, 20, 21, 22, 23, 24, and 25. The hospital was planning to include three new ORs. ORs run from Monday to Friday from 7:00 till 14:30 in its full capacity. On Wednesday, the ORs start working from 8:00; therefore, it is called the *late start day*. On this day, the nursing, anaesthesiologist, and nurse anaesthetists can organise their group meetings to update on new departmental developments and

[6] In German: Ärtzen im Praktikum
[7] In Latin: pro re neta (PRN) means "as the need arises"

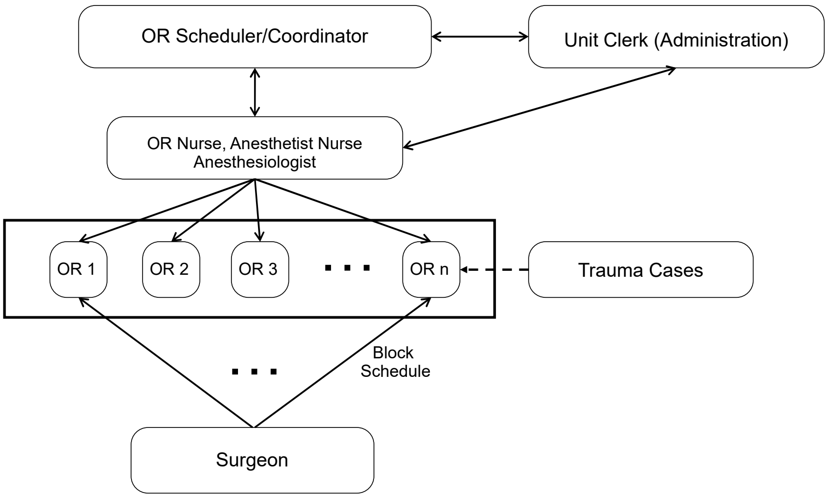


Figure 3.3: Illustration of block schedule for the surgeons at the hospital ORs and interaction of other actors for staff scheduling. Trauma cases receive priority in ORs

introduction of new medical rules and surveys.

3.2.3 Cost Drivers

The strategic direction of UMHC is to provide the best possible treatment for all patients, including those suffering from trauma and poverty as well as those under general conditions. Medicare, which provides insurance to senior citizens and permanent residents, and Medicaid, providing insurance to low-income group individuals and families, are two programs of the US government that provide healthcare solutions to the needy irrespective of their capacity to afford the service. Nevertheless, the UMHC would serve them without any assurance of recovering the service cost. The surgeons prefer to provide the best medical care irrespective of the costs incurred to the healthcare provider. It is because the regulations on healthcare services are remarkably stricter than in other domains. Any error can lead to lawsuits regarding incorrect practices. The physicians/surgeons are unaware of the actual costs and thus play a significant role in cost escalations.

3.3 Case of Action

It was observed in this study that the hospitals have more similarities when they are located within the same geographical location (such as the country), work culture, and business processes. The differences, such as in a transatlantic comparison between a German and an American hospital, appear as they operate in a completely different social, economic, and regulatory environment. Consequently, the next logical step would be to elucidate the underlying OR-WPS business process for both American and German cases so that an overview can be developed for further use. As with other domains, OR managements are interested in the ORs performing well and achieving the daily/weekly/monthly/yearly performance targets. The ORs perform evaluations based on classical value chain perspective in terms of productivity, quality, and cost of operations. On a high level, managements are interested in outputs, for example, how many patients were operated on and how much human resources were needed to run the ORs. In an OR, other detailed evaluations are performed. According to Bauer et al.[8], a few essential OR quantitative performance metrics are also of interest to managements. They include the number of surgeries and anaesthesia, percentage of elective surgeries, average anaesthesia time and incision-stitching time, average surgeon anaesthesia and OR nursing presence, the onset of anaesthesia presence, induction of anaesthesia, and first incision.

The average onset of the first incision can also be used as a metric, as can the sum of incision-suture time on call, ORs utilization, weekday distribution, and ORs demand. The number of empty times and changeover-times of the ORs also indicates the effectiveness of resource usage, as do on-time and the number of overtime hours. One approach to evaluate the OR performance entails measuring the aforementioned *operational* metric. For a proof of concept (PoC) and within the scope of the study, it is reasonable to measure only classical indicators and, in addition, a well-known value indicator known as *customer satisfaction*, as shown in figure (3.4). The circumference of the Key Performance Indicator (KPI) circle is a flexible membrane, which would change its shape depending on the values of the metrics; however, the total surface area of the circle would remain constant. This implies that if productivity improves, some other metrics should worsen, and vice versa.

[8] Source: M. Bauer et al. (2009), The German perioperative procedural time glossary [Bau+]

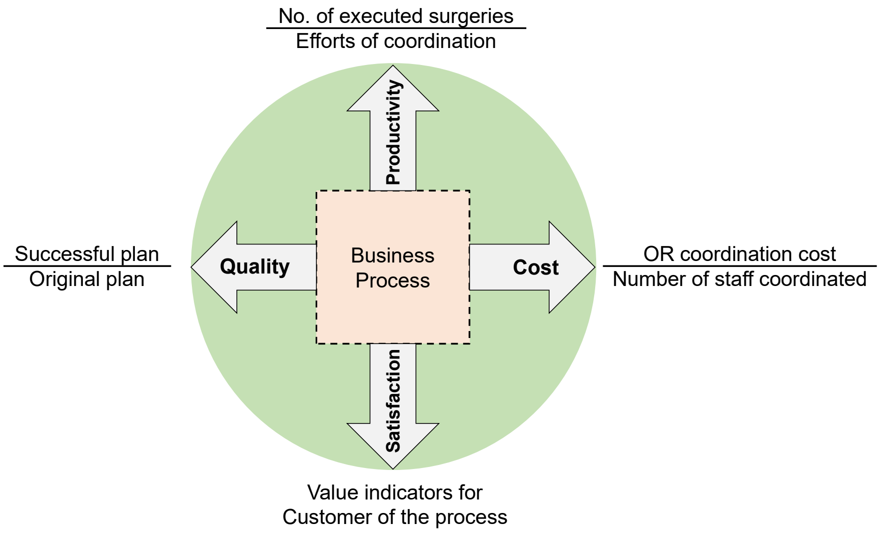


Figure 3.4: The quartet of key performance indicators for OR-WPS proof of concept simulation. The adjustable circumference is pushed out or pulled in by the measured values such as productivity, quality, cost, and customer satisfaction.

3.3.1 German Hospital

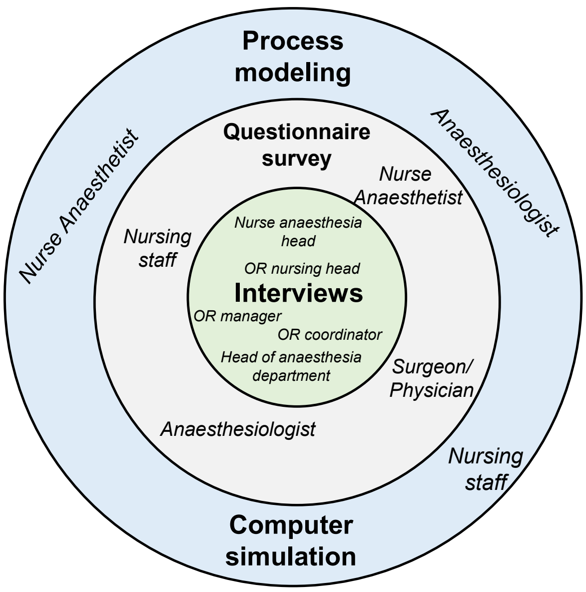


Figure 3.5: Illustration of a mixture of different methods to be employed to investigate the OR-WPS in German hospitals involved in the BELOUGA project

A few stakeholders were interviewed to understand the OR-WPS business process, as shown in figure (3.5). The figure also shows the mixture of different methods employed to gain an insight into the OR-WPS. The focus of this study was to understand the process followed by the German hospitals and which could form the basis to develop a computer simulation. The questionnaire results can be used to compare the American hospital, as described in section (3.3.2), with its German counterpart. Karl[9] reported a more detailed qualitative interview. Useful insight specifically into identifying customer value, its roles in process management, and customer roles can be found in the works by Stadtelmann[10] and Hastreiter et al.[11]. Therefore, the case of action in this study was to create a computer simulation that can measure the classical and value-based performance indicators. A simulation facilitates variability in input to simulate its influence on both classical and value-based outputs.

3.3.2 Missouri Hospital

In order to compare two hospitals in distant geographical locations perform the OR-WPS business process, interviews could be conducted with stakeholders, as shown in figure (3.6). The results can form a benchmarking comparison between a German and American hospital. Therefore, a customised questionnaire for Missouri was developed and used for survey. Furthermore, it is likely that real-world input data are required to mimic reality in the future decision support system of OR-WPS. A *work sampling* method could be employed to provide the probabilistic data for the computer simulation. Further, a business process model of an American case would be needed. Using a transcriptional method viewpoint, such as textual analysis of the interview data and work sampling, additional research questions on OR-WPS could be addressed. It may result from the *observational protocols* and their qualitative data analysis.

[9] Source: Marina Karl (2013), Value from the perspective of different customers in the healthcare sector - A qualitative study of surgical staff scheduling [Kar13]

[10] Source: Michael Stadtelmann (2018), Wert, Prozessmanagement und Kundenrollen im Gesundheitswesen [Sta18]

[11] Source: Stefan Hastreiter et al. (2015), Benchmarking-Studie OP-Personaleinsatzplanung [Has+15]

Figure 3.6: Illustration of a combination of various methods to be employed to investigate the OR-WPS at UMHS

4 Solution Approach and Method

Abstract: *This chapter details the use of various methods—literature review, computer simulation, business process discovery, work sampling, customer survey, content analysis, and EA—to achieve the objectives of this study. The research questions are presented preceding the description of the corresponding method. Details regarding the simulation software architecture, design, implementation, validation, and verification are also presented.*

4.1 Semi-Systematic Literature Review

On the basis of the insights gained from a previous work that entailed the simulation of another *enabling* business process[1], this study sought to refine the prior findings and identify the most appropriate simulation modelling approach, exhibiting characteristics such as *reliability*, *validity*, *implementation simplicity*, and *trustworthiness*. A *literature review*[2] can help prepare a conceptual foundation or any theory-building and groundwork for hypotheses formulation. Therefore, a *systematic literature review* (SLR) premise is an inquiry stating a (central) research question and associated sub-questions. The intention entailed a proper documentation of the questions, a timeline of execution, revelation of the outcomes, and their analysis so as to satisfy the reproducibility requirement of the results. The research questions considered for the literature review are as follows:

> *(Central) RQ1: Which is the most suited computer simulation method to fulfil the needs of this study?*

The following sub-questions followed this central RQ1:

[1] Source: Gaurang Phadke et al. (2015), Lerncockpit [Pha+15]
[2] Note: An overview of previously published research on a topic of interest.

(Sub) RQ: Which scientific process can be employed to outline the current state of the academic literature on the subject of interest of this study and to determine where the need for further investigation lies?

(Sub) RQ: Which one of the open-source or proprietary software development environments for computer simulation will conform to the goals of this study and will be able to address the research questions?

Grant et al.[3] have provided a typology of literature reviews, and one of them is a *systematic review*. A (Semi)-SLR was conducted[4] based on the method by Petticrew et al.[5]. Boren and Moxley[6] also reported on simple steps to pursue an SLR. These steps are as follows:

(a) Formulate the question and refine the topic,

(b) Search, retrieve, and select relevant articles,

(c) Assess quality followed by extract data and information,

(d) Analyse, synthesise data and information, and

(e) Write the systematic review.

SLRs are widely employed in the healthcare domain, whereas in the information systems management domain, the approach proposed by Webster and Watson[7] has been prominent. Based on these literary inputs, an approach as shown in figure (4.1) was adopted in this study. It is herein referred to as a Semi-SLR[8]. Through Semi-SLR, one can evaluate the types of simulation approaches employed, their applications, the outcomes and precise knowledge on the challenges faced by researchers

[3] Source: Maria J. Grant et al. (2009), A typology of reviews: an analysis of 14 review types and associated methodologies [GB09]

[4] Time-frame: At the beginning of this work from May 2015 till Nov 2022.

[5] Source: Mark Petticrew et al. (2006), Systematic reviews in the social sciences - A practical guide [PR06]

[6] Source: Suzanne A. Boren et al. (2015), Systematically reviewing the literature - Building the evidence for health care quality [BM15]

[7] Source: Jane Webster et al. (2002), Analysing the past to prepare for the future: writing a literature review [WW02]

[8] Note: To provide flexibility in the strictness of the process steps and exclude a few relatively less relevant references in the literature.

in developing the computer simulation models. It can enable efficient and effective implementation of ServiceSim OR-WPS simulation. The Semi-SLR was also employed over other approaches to obtain evidence of the technology in the literature, identify the gaps, if any, and prepare a basis for simulation model development. In the following sections, the central and sub *research questions* are sequentially addressed.

4.1.1 Method

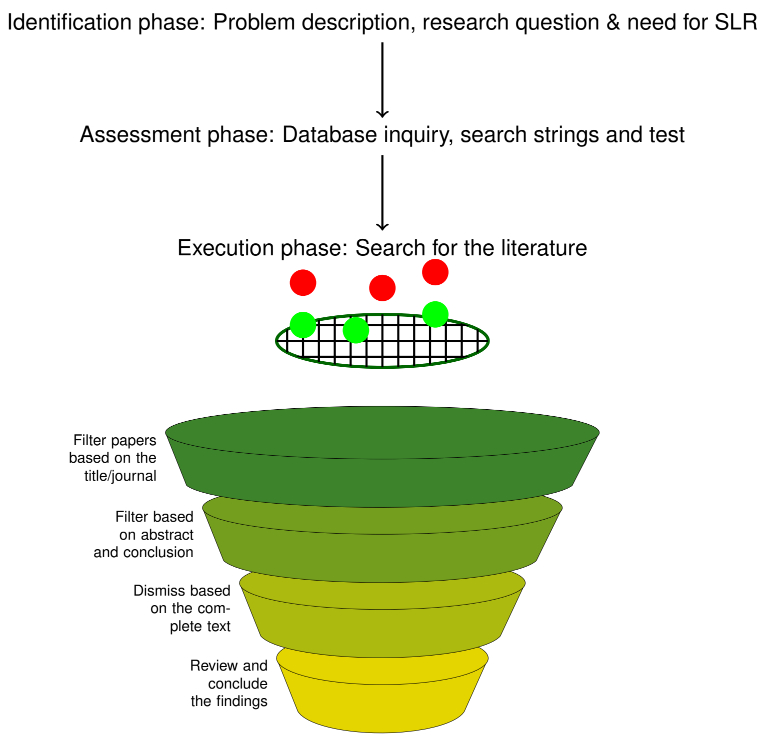


Figure 4.1: A step-by-step approach was adopted for the Semi-Systematic Literature Review

An overview of the Semi-SLR adopted in this study is depicted in figure (4.1). In the first step, the RQs were formulated, and the need for the Semi-SLR was investigated. In the second *search for, retrieve, and select relevant articles* step, after consulting the (health science) libraries of the University of Bayreuth and UMHS, the Semi-SLR was meticulously planned and executed. It comprised the following sub-steps:

(a) establishing the keywords and search terms,

(b) test searches,

(c) experimenting with the extraction of data, and

(d) subsequent improvement in any previous or following steps.

In the third *assess quality* step, the Semi-SLR rules concerning inclusion, exclusion, and extraction were secured and specified. The fourth step, which is to *extract data and information* using scholarly databases, is explained in Chapter (5), section (5.1).

4.2 Simulation of the OR-WPS Process

The core deliverable of this study is the *ServiceSim* OR-WPS, which is a multi-agent simulation model of OR-WPS. The goal essentially was to deliver a simulation model that fits its purpose. Before performing any simulation implementation and experiment in this study, the following research questions were posed:

> *(Central) RQ2: How can a multi-agent simulation of OR-WPS be practically implemented, and in which manner will it act as a decision support system?*

The following sub-questions followed the central RQ2:

> *(Sub) RQ: Which observations and scenarios can be used from the real world to design the simulation model and experiment? What can we learn from them in practice?*

> *(Sub) RQ: Which input parameters impact the simulated business-process KPIs, whether positively, negatively or neutrally, and why?*

> *(Sub) RQ: Which combination of input parameters creates results that are outliers, and why?*

4.2.1 Method

In order to elucidate the process of realising a computer-simulation model, an overview of the phases followed in this study, beginning with *planning* till *output analysis*, are depicted in figure (4.2)[9]. These phases are elaborated herein as follows: business process discovery in section (4.2.2); software architecture in section (4.2.3); formulae and heuristics in section (4.2.4); software design and implementation in section (4.2.5); simulation output variables and dashboard in section (4.2.6); and simulation verification and validation in section (4.2.7).

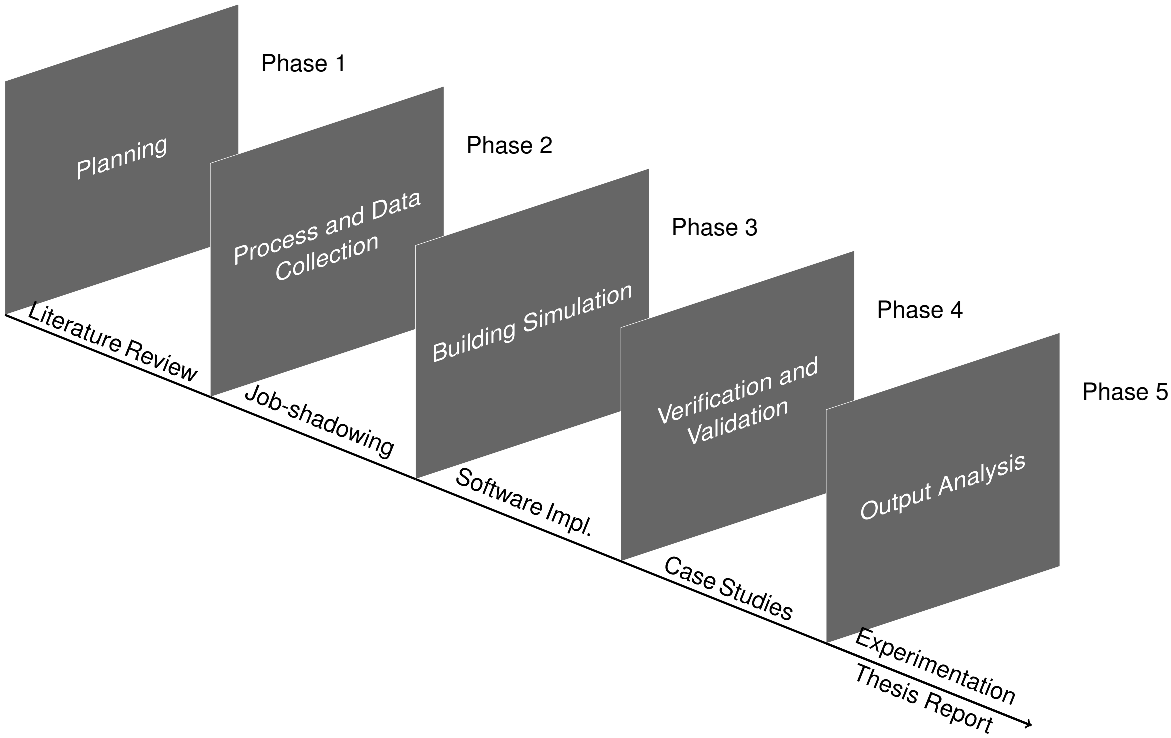


Figure 4.2: Research process followed in this study—from planning phase to output analysis

4.2.1.1 Phase 1: Planning

In the first step, the *planning phase* or phase 1, the RQs were formulated, and a Semi-SLR, defined in section (4.1), was conducted to address them, as described in results section (5.1). The core question in the *planning* phase was "to determine the simulation approach in the area of business process simulation within the healthcare domain". The outcome of the literature review indicate that the multi-agent simulation

[9]Time course of events in an experiment by Rudolf Siegel (https://texample.net//tikz/examples/events/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

based on off-the-shelf software is suitable for this study. Therefore, the model was implemented in AnyLogic Personal Learning Edition (PLE).

4.2.1.2 Phase 2: Process and Data Collection

In the second step, the *process* and *data-collection* phase, through job-shadowing[10], the purpose of this thesis was explained to the stakeholders in hospitals in Germany and thereafter in Missouri, USA. With an agreement on the two projects named BELOUGA and BELOUGA-M, a series of job-shadowing was performed to gather the problems faced by healthcare service providers. In order to comprehend the current business process, a series of interviews was conducted with the identified process stakeholders of the hospitals. A series of *exploratory* interviews was prepared and conducted with the research partners of BELOUGA. These interviews were scientifically analysed in BELOUGA to perform follow-ups. Specifically for the computer simulation, both telephonic and personal interviews were conducted with the OR-WPS enabling process stakeholders. Several documents related to the business process were collected, anonymised, and analysed for use in the next phase. The surveyed OR-WPS enabling business process is described in section (4.2.2). Subsequently, a work-sampling was performed at the hospital in Missouri, USA, which could be used as input data in future simulation studies, as explained in section (4.3), with the corresponding results in section (5.4).

4.2.1.3 Phase 3: Building Simulation

The process and data collection phase followed the modelling and simulation phases. The models were built based on the business process discovery, as discussed in section (4.2.2). Based on the high-level software design of the ServiceSim OR-WPS, discussed in section (4.2.3), the mathematical formulae and heuristic approaches in section (4.2.4) were implemented, together with a visual dashboard for user inputs in section (4.2.6).

[10] In German: Hospitation

4.2.1.4 Phase 4: Verification and Validation

As detailed in section (4.2.7), the simulation model was verified with the stakeholders using live demos and the obtained results on the test use cases. Further, it was validated with the potential users, followed by a few case studies developed to showcase its results, based on the method detailed in section (5.3). Simulation models must be continually tested for new input parameters and deployed as they are only approximations of reality. The limits of the simulation model with regard to this study are highlighted and briefly discussed in section (5.3.5).

4.2.1.5 Phase 5: Output Analysis

As explained in the description on the design of the experiment in section (2.1.4), if there are a few (input) factors in an experiment, the effects could be a set of possible outcomes. To derive the settings in order to obtain the simulation results, it was assumed in this study that a simulation is an experiment and that several trials are needed before reliable answers to the RQs can be attained. As a result of the experimental design in this study, the simulation could be simply managed with a focus on the following two directions:

(a) investigation of responses due to variation of each factor that are independent of each other in the simulation experiment

(b) a response and its interpretation based on the factors that have a combined effect

As for the following sections, section (4.2.2) first provides an in-depth examination of the method to reveal the OR-WPS business process. Thereafter, the software architecture is detailed in section (4.2.3); the mathematical formulae and heuristics are described in section (4.2.4); the design is detailed in section (4.2.5); the actual implementation is explained in section (4.2.6); and the verification and validation of the simulation program is described in section (4.2.7). Furthermore, section (5.3) in Chapter (5) presents the experiments performed and analyses of the output.

4.2.2 Business Process Discovery

The section introduces the methods used to discover the *current state* of the business process both in Germany and the USA, followed by their outcomes in the form of ArchiMate® diagrams. German and American healthcare systems differ in many aspects. From the concepts of universal healthcare, customer satisfaction, and autonomy to specific stakeholders of the service system, an interesting comparison can be made from the perspective of the business process. In order to discover the business process, several rounds of interviews with the key stakeholders were required. Interviews were conducted with the German and American healthcare service providers in this study. Therefore, the language of the interviews and respective process maps were created in German and English. To conduct the interviews, several prior studies in the literature were referred to. For example, the work by Glaeser et al.[11] aided in expert interviews; and the study by Mayring[12] was helpful with regard to *qualitative data analysis* (QDA). Further, Meuser et al.[13] reported on how to conduct an expert interview, and Seidman[14] reported on *interview techniques*. Before conducting the interviews, the interviewee were assured that their data would be protected. The interviews sought to positively impact the organisation. Otherwise, one might risk losing the trust and sponsorship of the critical process stakeholders.

Before the analysis, three sets of questionnaires were designed and posed to the OR-WPS stakeholders. The questionnaire was focused on three clusters of aspects. As indicated in table (4.1), the first inquiry was regarding the people involved in the OR-WPS, their product/service, and the process followed. Through a few of pre-session interviews, contact with the process-relevant functional representatives, namely, the OR scheduler, OR manager, representatives from nursing, nurse anaesthetist, and representatives from anaesthesiologist departments, was established. Owing to the iterative nature of the knowledge-gaining procedure, one or more interviews were usually conducted. Each functional representative was briefed regarding

[11] Source: Jochen Gläser et al. (2010), Experteninterviews und qualitative Inhaltsanalyse - Als Instrumente rekonstruierender Untersuchungen [GL10]

[12] Source: Philipp Mayring (2010), Qualitative Inhaltsanalyse - Grundlagen und Techniken [May10]

[13] Source: Michael Meuser (2009), Das Experteninterview - konzeptionelle Grundlagen und methodische Anlage [MN09]

[14] Source: Irving Seidman (2013), Interviewing as qualitative research - A guide for researchers in education and the social sciences [Sei13]

the present study, its purpose, and expected outcomes. In the interview sessions, the terms of the business used, activities performed by the participants, and their overall understanding concerning the other functions and their working were enquired. The advantage of briefing the other functional representatives about the findings, along with personal data protection assurance, was to have transparency and avoid the silo effect. As indicated by table (4.2), the second cluster of questions concerned activity sequence and performance by location. The third set of questions focused on activity sequence and performance by location, as indicated by table (4.3).

Classification	*Question*	*Follow-up*
People	What is your job title and responsibility?	Who are the other people you interact with to fulfil the tasks?
	How much experience do you have in this specific job?	Can somebody else perform these tasks?
Subject-matter	Which are the essential enabling business processes at the hospital?	Why would one consider them as necessary?
		Can one choose the top three of these for further investigation?
		Are the organisational vision and corresponding strategic direction directly or indirectly impacting the processes?
		Can one identify the process owner, stakeholders and its customers?
	What is specific responsibility vis-à-vis OR staff scheduling?	Has the organisation ever tried to improve its performance, measure customer satisfaction and similar concepts?
Purpose	Can one identify the potential improvement opportunities in these processes?	Is the hospital interested in cooperating if we survey the workforce, model a business process, and critically analyse through a computer simulation technique?
		How to obtain regulatory approval from the institutional review board? Will the colleagues at the hospital will support the measurement of customer satisfaction?

Table 4.1: Interview—general inquiry of the people, process, and product/services (based on one of the outcomes of BELOUGA project)

Classification	*Question*	*Follow − up*
Sequence	To manage or execute the process, which kinds of activities does one perform annually, half-yearly, quarterly, weekly or daily?	Which other functional departments perform activities for the process to work?
		Is the process currently running satisfactorily, and if any measured performance based on customer surveys done in the past?
	Can one think of a couple of activities that can be eliminated or modified to streamline the process?	Which kind of impacts would these changes have on the current state of the process in physical and monetary terms?
		Do the activities have concurrency and deadline to communicate or report to other stakeholders?
Location	Are the activities and functions distributed among different service sites of the provider?	How does one communicate among the decision-makers and relevant to the stakeholders?
		Is any meeting taking place daily, weekly, or on other time scales to decide on staff schedule preparation?

Table 4.2: Interview—discover the OR staff scheduling supporting process, stakeholder communication and coordination (based on one of the outcomes of BELOUGA project)

OR-WPS process areas were initially modelled in Architecture Animate (ArchiMate) language and subsequently in BPMN. The ArchiMate® models specifically aimed to establish a relationship between the business stakeholders (without roles in the organisation) and the business process (as-is) without detailing the business functions and data objects. Another purpose of these models was to realise communication with business stakeholders for validation. Based on these inputs and after a series of iterations, the final process maps were delivered. These maps are also known as workflow models, and they describe how all process participants interacted, communicated, coordinated, and performed the specific activities. These activities lead to calculations of classical KPIs such as productivity, quality, and cost. The advantage of the adopted iterative approach is manifold—faster delivery, change accommodation, acceptance, and adoption. The process discovery results are presented in chapter (5), section (5.2).

4.2.3 Software Architecture

An appropriate context for the term *architecture* as used in this section is as described by Bass et al.[15] and highlighted in the following definition (4.19):

Definition 4.19. *Software Architecture*

> *"The structure or structures of the system, which comprise software elements, the externally visible properties of those elements, and the relationships among them." [BCK13]*

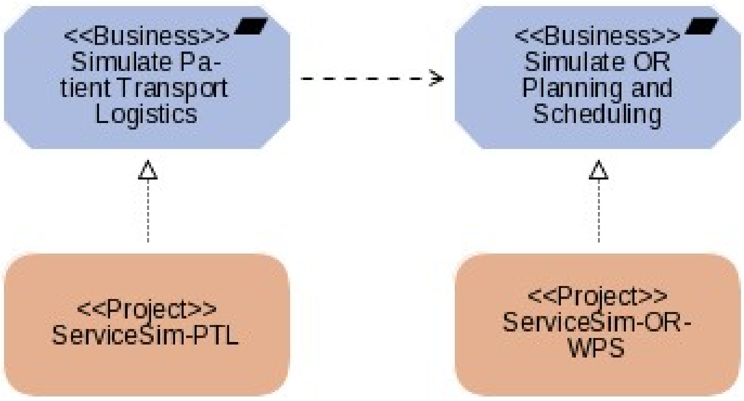


Figure 4.3: A view of high-level requirements and the need for specific projects to fulfil the individual requirements modelled in ArchiMate® language

Software architecture modelling was employed to gain insights into and overall grasp on the eventual "implementation" or "procuring *off-the-shelf* and customisation" of the simulation model, satisfying architecture principles of an enterprise and business requirements of the end user. Another purpose of using *software architecture* discipline in this study was to ensure that appropriate software design, patterns, guidelines, and relevant development tools were used to enable the simulation of OR-WPS. OR-WPS enabling process simulation required a decentralised software application, which can yield dynamic responses and can interact with other application components. It should create agent who have goals and behave as well as negotiate to achieve their objectives. Based on such software architecture requirements, a *multi-agent simulation* approach was found to be more suitable than DES[16].

[15] Source: Len Bass et. al. (2013), Software architecture in practice [BCK13]
[16] Source: Danny Wynes (2010), Architecture-based design of multi-agent systems [Wey10]

In order to choose the right tool for the multi-agent simulation of OR-WPS, the available options that satisfy the architecture principles were examined. A review of multi-agent simulation tools by Nikolai[17], Kravari[18] and Abar[19] also supports this selection process, as mentioned in section (5.1). A portfolio base analysis, as mentioned in figure (5.5) in chapter (6), for the software development for multi-agent simulation of OR-WPS, can be created and evaluated[20]. Figure (4.3) illustrates the two (research) projects that supported two distinct business (research) requirements, namely supporting OR-WPS and PTL as DSS. The ServiceSim OR-WPS is the tooling name for the enabling process. A clear distinction between *software architecture* and *software engineering* was followed in this study. As mentioned in Schmutzler[21], software architecture afforded a strategy to address multiple business and technological requirements. In contrast, software engineering facilitated the iterative examination of the software-architecture plan or design and enabled a software implementation in the (to-be used) programming language suitable to the plan. The *software specification* enabled the gathering of the required functionality and constraints of the multi-agent simulation. The actual *design and implementation* and its outcomes are discussed in section (4.2.5). In the following section (4.2.4), the various mathematical formulation and heuristics implemented in the ServiceSim OR-WPS are detailed.

4.2.4 Formulae, Heuristics and Variables

The mathematical formulations are explained in section (4.2.4.1), followed by an explanation of the heuristics in section (4.2.4.2) and input variables in section (4.2.4.3).

[17] Source: Madey Nikolai et al. (2009), Tools of the trade: Survey of various agent based modeling platforms [NM09]

[18] Source: Kalliopi Kravari et al. (2015), A Survey of agent platforms [KB15]

[19] Source: Sameera Abar et al. (2017), Agent based modeling and simulation tools: A review of the state-of-art software [Aba+17]

[20] Note: This figure's findings, conclusions, and recommendations strictly correspond to this study and cannot be generalised.

[21] Source: Adrian Schmutzler (2015), Entwicklung eines Simulationsprogrammes zur Evaluation und Optimierung der OP-Personaleinsatzplanung in einem deutschen Krankenhaus [Sch15, p. 7]

4.2.4.1 Mathematical Formulae

The *demand* of the number of (workforce) resources must be calculated before performing the simulations. The starting point was to estimate the *number of the surgeon* required, equal to the product of *number-of-ORs* and the *average* number of surgeons required in the ORs but taking vacation-related buffer into account as explained in the following equation (4.1). Theoretically, if 20 surgeons are needed to run the daily ORs of a typical hospital, and if the planned buffer is 5%, we would effectively have 19.05 surgeons available on a day, as indicated by the calculation based on equation (4.1).

$$\boxed{\#tot = \frac{20}{(1+0.05)}} \tag{4.1}$$

Based on this total (#tot), the number of surgeons (#avail) available can be calculated; this is listed in table (4.5). Further, in section (2.2.3), the expressions for (service) productivity, (service/workforce) cost, (service) quality, and (service) customer satisfaction is provided. The formulations slightly deviate in the actual implementation; this aspect is also explained. The productivity, referred to as *service productivity*, is calculated as “the ratio between the number of successfully planned and scheduled surgeries to the time required for planning them", as expressed by equation (4.2). Notably, the focus here is on calculating the productivity of the scheduling/planning process. The variables introduced in the equation are defined following the mathematical formulation of equation (4.2).

$$\boxed{\textit{Service productivity} = \frac{OR_{act}}{t_{total}} = \frac{H_{act} \times OR_{hall}}{t_{total}}} \tag{4.2}$$

where

OR_{act} = Successfully planned/scheduled surgeries
t_{total} = Total time required to plan and schedule the surgeries
H_{act} = Number of operating theatres (actually) planned and scheduled
OR_{hall} = A factor for the correct unit, i.e. surgeries per unit time

Equation (4.2) can be used to calculate productivity; however, the goal in this study was to calculate the average productivity for a given simulation time. It can be calculated as “summation over the ORs planned/scheduled daily to the summation over total time required to plan and schedule the surgeries", as expressed by equation (4.3).

$$\text{Service productivity} = \frac{\sum_i^N H_{act,i}}{\sum_i^N t_{total,i}} \times OR_{hall} \tag{4.3}$$

Similarly, the cost of running the OR-WPS process of scheduling the ORs with the workforce and the number of ORs can be calculated using equation (4.3). Logically, the *service cost* can be calculated by "time required for planning/schedule by an agent (a) multiplied by a cost factor (c_a) based on the salary by the planner/scheduler". Mathematically, summing over all agents (A) and several simulation days (N), we get equation (4.4) to calculate the service cost.

$$\text{Service cost} = \sum_a^A \sum_i^N t_{a,i} \times c_a \tag{4.4}$$

where

$t_{a,i}$ = Time required to plan/schedule the workforce by agent (a)
c_a = Cost factor with only internal workforce
N = Number of simulation-days
A = Agents involved in planning/scheduling

In order to ensure that the scheduling of *external workforce* to run the planned/scheduled ORs is considered numerically, the additional payment to external workforce, who are usually costlier than the internal workforce (per unit workforce), is considered[22]. As mathematically shown in equation (4.5), an additional term is accounted for the externals, in contrast with equation (4.4).

$$\text{Service cost} = \sum_a^A \sum_i^N t_{a,i} \times c_a + \sum_i^N d_i \times c_{ext} \tag{4.5}$$

where:

c_{ext} = The cost factor for the external workforce
d_i = Activities or workload performed by an external workforce

[22]Note: The externals would be scheduled when the original plan/schedule cannot be executed owing to lack of internal workforce or opening of additional ORs during a day.

The cost incurred for planning/scheduling the(*number of planned*)/(*scheduled surgeries*) performed for the number of simulation days can be normalised as shown in equations (4.6) and (4.7), respectively.

$$\boxed{\text{Cost per surgery} = \frac{\text{service cost}}{\sum_i^N H_{act,i} \times OR_{hall}}} \tag{4.6}$$

$$\boxed{\text{Cost per day} = \frac{\text{service cost}}{N}} \tag{4.7}$$

On the basis of the explanations herein and its application with regard to OR-WPS, *service quality* is defined as "the success rate at which planners could plan and schedule the surgeries". This implies that if there is a drop in planned surgeries because of the unavailability of staff due to unexpected reasons, the quality of the service would degrade and vice versa. Owing to its design, the simulation did not consider the surgery cases on the day of its actual execution that get cancelled because of unanticipated factors such as surgery case delays and cancellation due to legal restrictions on the must-have workforce with skills.

$$\boxed{\text{Service quality} = \frac{OR_{act}}{OR_{init}} = \frac{H_{act} \times OR_{hall}}{H_{init} \times OR_{hall}} = \frac{H_{act}}{H_{init}}} \tag{4.8}$$

where:

OR_{init} = initially planned/scheduled ORs
OR_{act} = Successfully planned/scheduled surgeries

To calculate the average value of service quality over the simulation days, one can perform a summation over the last expression in equation (4.8) and use the equation as shown in (4.9).

$$\boxed{\text{Service quality} = \frac{1}{N}\sum_i^N \frac{H_{act,i}}{H_{init,i}}} \tag{4.9}$$

The formulations presented in this section were used to calculate the *classical* KPIs. However, the complex part of the study was to propose a procedure to calculate the *value-based* KPIs such as *customer satisfaction*. This aspect is discussed in the following section (4.2.4.2).

4.2.4.2 Customer Satisfaction Heuristic

According to Hill et al.[23], *customer satisfaction* can be defined as “a measure of how an organisation’s total product performs in relation to a set of customer’s expectations". In social sciences, one can identify a value chain and the meaning of specific satisfaction to the customers of the value chain through interviews; design and perform the survey; report the results; and make future changes for improvement[24]. Customer satisfaction measurement, based on the aforementioned steps, is a well-understood topic in service-oriented domains such as healthcare. However, it can be a challenge to be incorporated in the value-chain/process modelling and simulation. There have been many efforts to model customer satisfaction, either to reproduce (any) measured value or model a procedure for predicting its value. The same challenge was posed in this study and can be described as follows:

> *How can the customer satisfaction of the OR-WPS process be calculated and then measured in a simulation model?*

According to Zondiros et al.[26], “simulation of social phenomena or activities is a quite difficult task since there are so many considerations (not all well understood) involved. There are two types of models used, the analytical ones and those that use artificial intelligence techniques.". Further, Zondiros et al. reported, “the analytical models usually lead to a system of differential equations, which can be efficiently solved numerically using advanced methods". They also stated, “neural networks, fuzzy logic or stochastic techniques can be used to account for complicated models". A review of the literature for algorithms to computationally provide a value of customer satisfaction for OR scheduling and planning did not yield any results. Therefore, in this study, a heuristic approach was considered more valuable. Romanycia et al.[27] presented a good review of the definition of a heuristic.

[23] Source: Nigel Hill et al. (2017), The handbook of customer satisfaction and loyalty measurement [HA17]
[24] Note: In this study, the inputs for these steps were taken from the BELOUGA research project[25] and, therefore, are not treated in detail herein.
[26] Source: Dimitris Zondiros et al. (2007), A simulation model for measuring customer satisfaction through employee satisfaction [Zon+]
[27] Source: Marc Romanycia et al. (1985), What is a heuristic? [RP85]

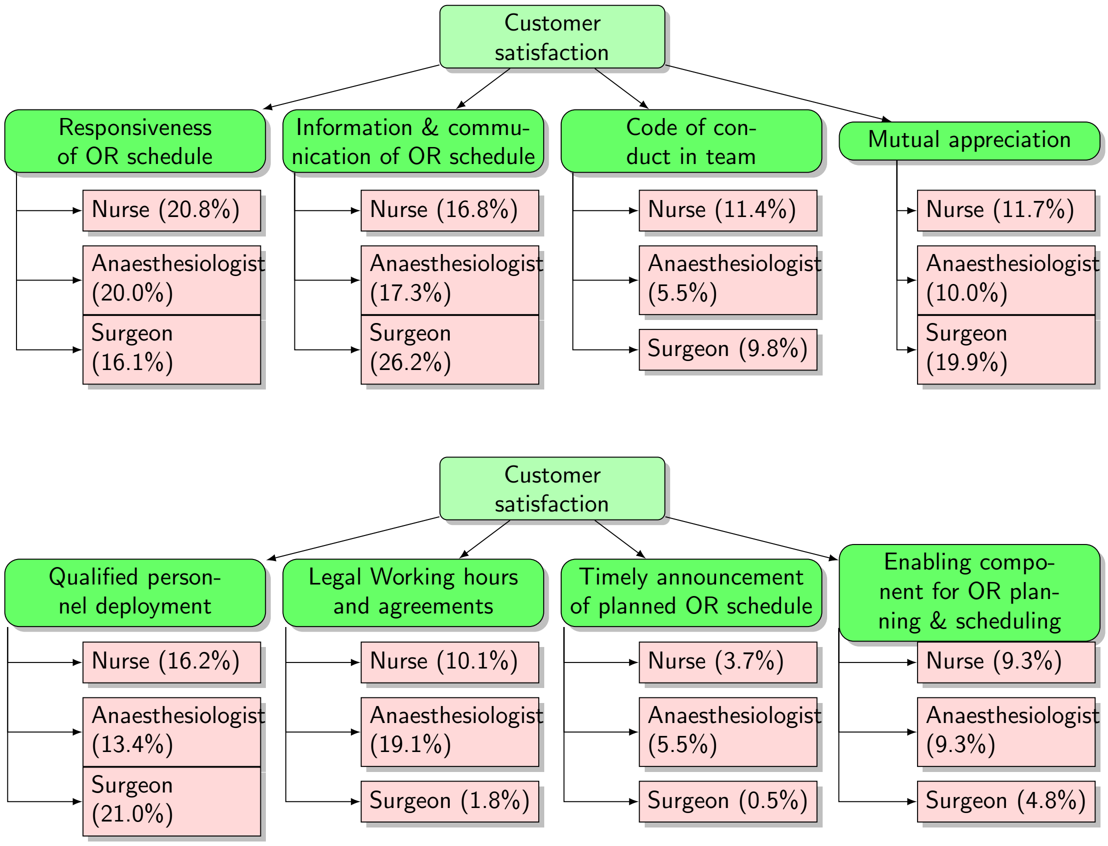


Figure 4.4: A tree diagram depicts the results of a survey conducted in the BELOUGA project indicating the percentage of contribution of individual value dimensions of different staff groups to overall customer satisfaction in German hospitals

Responsiveness of the OR schedule

The *responsiveness of the OR schedule* is heuristically calculated using two new variables, d_{diff} and d_{vac}, denoting *difference* and *vacation*, respectively. In a hospital, if the number of personnel of an organisational group (such as nursing) is less than the minimum required personnel to run the ORs properly, the OR coordinator must make the appropriate decision. An unplanned event (such as illness or sudden absence) may be addressed by the OR coordinator (responsible for nursing) by replanning the vacations for the remaining employees who would be available. A measure, therefore, is taken to request and cancel a staff member's vacation and compensate it with another in the future. For each group of staff, a variable d_{vac} indicates sum up of these shortages to be used in future calculations. As a result, d_{vac} must be set for the total number s_q of individuals employed in the respective department q for evaluation. As each organisational group (such as nursing) would impose distinct personnel constraints, ranging from a high number of rescheduled days for one department and a lower one for another, the value of d_{vac} must be computed at an organisational group level (such as nursing). The outcome is a distinct value of *customer satisfaction*. The variable d_{diff} keeps track of these dynamics and can be defined as the difference between the maximum and least values of d_{vac} at a given time. Mathematically d_{vac} can be calculated as described in equation (4.10).

$$\boxed{d_{diff} = \max_{q \in D} \frac{d_{vac,q}}{s_q} - \min_{r \in D} \frac{d_{vac,r}}{s_r}} \tag{4.10}$$

where:

D = Organisational group or department
d_{diff} = Difference between maximum and minimum
d_{vac} = Sum-up of vacation for an organisational group
s_q = Number of personnel in a group

The quantity d_{diff} is a global (computational) variable; this implies that its value is identical for all the groups. This variable is kept as *global* because the variations in workforce availability due to unplanned events (such as illness or sudden absence) is the overall amount of changes in shortage situations, not the actions performed by OR schedulers/coordinators of different organisational groups. Further, the satisfaction for responsiveness of OR schedule $sat_{resp,q}$ of a department q is as described in equation (4.11).

$$\boxed{sat_{resp,q} = 1 - \left(\frac{1}{DOY}\right).f_{vac}.\left(\frac{d_{vac,q}}{s_q}\right) - \left(\frac{1}{DOY}\right).f_{diff}.d_{diff}} \tag{4.11}$$

where:

$sat_{resp,q}$ = Contribution to overall satisfaction due to the responsiveness of OR schedule
$fvac$ = Normalisation factor
f_{diff} = Normalisation factor

As the model based on this heuristic can be used to simulate a year (approximately 250 working days per year), it was reckoned that a value of 10 or more days per person results would artificially create almost zero value for satisfaction in terms of both

d_{vac} and d_{diff}. This would result in a f_{vac} and f_{diff} producing value of approximately 0.1[28]. Finally, the calculation of the value for $sat_{resp,q}$, taking into account the possible negative numerical values of $sat_{resp,q}$, is as shown in equation (4.12).

$$\boxed{sat_{resp,q} = \begin{cases} sat_{resp,q}, & \text{if } sat_{resp,q} > 0 \\ 0, & \text{otherwise} \end{cases}} \tag{4.12}$$

Information and communication of the OR schedule

The *information and communication of the OR schedule* is heuristically calculated based on the event-based and the lost opportunity-based components. As mentioned in the previous section, the number of vacations (due to illness or sudden absence) were measured; it is also possible to determine how many times a situation with fewer staff resources occurs, which ultimately contributes to the OR schedule. Several counters[29] numerically measure these events[30] are introduced. These are, for instance,

(a) How many times an OR cannot be run due to shortage of workforce denoted by e_{def}?

(b) How many staff shortage events are handled by OR coordinator denoted by e_{ext}?

(c) How often the organisational groups such as a nursing department denoted by q handled shortage themselves and can be weekly $e_{week,q}$ or daily $e_{day,q}$?

The sum of these e terms can be expressed as in equation (4.13).

$$\boxed{e_{all,q} = e_{def} + e_{ext} + e_{week,q} + e_{day,q}} \tag{4.13}$$

The second component contributing to this part of customer satisfaction is the loss of opportunity due to an unfavourable situation. In practice, surgeries are cancelled

[28]Note: It is numerically acceptable for both f_{vac} and f_{diff} to take up a value of 5.

[29]Note: A counter can store how many times something occurred, and the counting (re)starts with the initial value as the numerical zero.

[30]Note: An event herein implies an occurrence when adding personnel or resolving a resource conflict is required to run an OR. The event variable is the counter. A normalisation of event variables is not required as these are not dependent on the number of personnel in the corporate group.

because the minimum necessary staff to start an OR are not met, maybe because of insufficient personnel in one of the organisational groups at a specific time during a job shift. It is denoted by $d_{lost,q}$ and represents sufficient presence from one group but insufficient from another[31]. A lost opportunity is because of the *not-so-good* plan and therefore contributes to satisfaction indicators of information and communication of OR schedule. After normalisation based on several employees s_q and several days passed in a year N, its value can be obtained using equation (4.14).

$$p_{lost,q} = \frac{d_{lost,q}}{s_q.N} \tag{4.14}$$

The result of the equation represents a percentage of time wasted but not the value of satisfaction. It does not require scaling with $1/DOY$. However, it needs to be transformed to customer satisfaction by using an equation as shown in (4.15) and can be characterised as a step-curve. The behaviour of the curve below 10% indicates no effect on customer satisfaction; and linearly increasing beyond 10% till 30%; and zero customer satisfaction contribution above 30%.

$$sat_{lost,q} = \begin{cases} 0, & \text{if } p_{lost,q} < 10\% \\ 5.(p_{lost,q} - 0.1) & \text{if } 10\% \leq p_{lost,q} \leq 30\% \\ 1, & \text{otherwise} \end{cases} \tag{4.15}$$

Equations (4.16) and (4.17) show the calculation of the sum of all contributions to customer satisfaction for the value dimension *information and communication of the OR schedule*. They also show how to perform a choice of the final value of Q if the value calculated in equation (4.16) outputs within a specific range respectively[32].

$$sat_{info,q} = 1 - \left(\frac{1}{DOY}\right).f_{event}.e_{all,q} - sat_{lost,q} \tag{4.16}$$

$$sat_{info,q} = \begin{cases} sat_{info,q}, & \text{if } sat_{info,q} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{4.17}$$

[31]Note: For example, the OR nurse is available, but the nurse anaesthetist is missing.
[32]Note: An equation as in (4.17) outputs a step function.

Qualified personnel deployment

In healthcare, all medical staff working in an OR are suitably qualified and skilled. However, what makes a difference is the day-before or intra-day availability of specialists in a particular medical task—a must for a scheduled surgical operation and thus contributing to a well-executed medical operation. Therefore, workforce qualification is the OR-WPS process-independent and necessary condition to work. Consequently, how qualified the workforce is does not need to be considered in a simulation. Instead, it can be calculated from the proper deployment and allocation of a skilled and experienced workforce. The workforce here implies nurses, nurse anaesthetists, and anaesthesiologists. Therefore, a value of $sat_{qual,q}$ can be calculated numerically based on two inputs, i_{qual} and $sat_{calc,q}$, as shown in equation (4.18).

$$\boxed{sat_{qual,q} = 0.5.\left(i_{qual}\right) + 0.5.\left(sat_{calc,q}\right)} \tag{4.18}$$

The computation comprises two factors. First, it is assumed that the presence of external staff to fill in the staff shortage would most likely degrade the overall satisfaction of the internal staff due to someone not being familiar with a group task. Therefore, a variable p_{ext} is introduced, which calculates externals' total quantity of work d. Further, d is divided by "the product of the number of days elapsed N and the available ORs H". The p_{ext} is the average number of externals per OR per day, as shown in equation (4.19).

$$\boxed{p_{ext} = \frac{\sum_i^N d_i}{H.N}} \tag{4.19}$$

The second factor is the effect of spare time or lost working time. As most medical workforce are generally (highly) qualified, the workforce can interpret its underutilisation as a form of *non-appreciation* of its medical skills. The equation as shown in (4.19) is reused to calculate this factor. When combined, equation (4.20) results and can be used to calculate the contribution to overall customer satisfaction due to *qualified personnel deployment* in the OR-WPS.

$$\boxed{sat_{calc,q} = 1 - \left(f_{ext}.p_{ext}\right) - \left(sat_{lost,q}\right)} \tag{4.20}$$

The factor f_{ext} used in equation (4.20) is set to value 1 if each OR has at least one external staff and values satisfaction to zero. The negative value of $sat_{calc,q}$ has to be discarded. Thus, the final value of $sat_{calc,q}$ used in the simulation would be obtained based on equation (4.21).

$$sat_{calc,q} = \begin{cases} sat_{calc,q}, & \text{if } sat_{calc,q} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{4.21}$$

Remaining value dimensions

Reasonable linkages to simulation parameters such as code of conduct in a team, mutual appreciation, legal working hours and agreements, and enabling components for OR planning and scheduling as shown in figure (4.11) could not be found for the four additional satisfaction components. Therefore, further investigation is needed. They must be manually specified before the simulation begins by selecting an integer value from 1 to 5. The examination is carried out globally, with no distinction made between departments other than through weighting considerations.

Combined value of customer satisfaction

In the BELOUGA survey in Germany as shown in figure (4.4), it was revealed that the nursing workforce OR schedule's responsiveness weights were 20.8%, information and communication of the OR schedule was 16.8%, and appropriately qualified staff or personnel deployment was 16.2%. The other weights for factors such as mutual appreciation, code of conduct in the team, legal working hours and salary standards, supporting components for the planning and scheduling, and timely notification of personnel deployment was 46.2% altogether. In the following subsections, these aspects are explained and discussed based on cause-effect relationships and interactions. Discussions on possible enablers to improve their contribution to the customer's overall satisfaction are provided thereafter.

4.2.4.3 Exception Handling

On the basis of the inputs mentioned in the previous section (4.2.4.2) and their incorporation, as shown in the following section (4.2.5.2), one requires (artificial) logical steps to calculate the weekly to daily resource requirements and imitate the reality. Exception handling must be in place to catch any numerical error due to approximations in the simulation. The numerical challenges faced during the creation of algorithms were as follows:

(a) Owing to mathematical calculation, the result of “number of resources" could be a *decimal number*. The numerical workaround in the simulation was solved by declaring the number of resources and counter-for-the-simulation-days using *floating-point* numbers. Thus, one can mitigate the risk beyond any established boundaries or prescribed limits due to round-off or computational error.

(b) The vacation days taken by the members of the workforce would have to be compensated for in the simulation.

(c) The thread of control in the time (i.e. decisions on a yearly, monthly, weekly, daily level) should be passed from one to another agent based on their job description. For instance, the weekly and daily decisions are taken by OR coordinator/scheduler (agent).

(d) During simulation, to keep the OR operational costs under control, the need for an external resource to keep the OR running was introduced before any simulation experiment took place.

In table (4.4) are the variables which were identified and can be input to the ServiceSim OR-WPS multi-agent simulation. Section (4.2.6) can see the implemented dashboard in figures (4.14), (4.15) and (4.16) for these variables.

4.2.5 Software Design and Implementation

The high-level design of the ServiceSim OR-WPS is based on a software chain comprising the simulation program inputs as explained in section (4.2.5.2), processing of these (inputs) in a multi-agent simulation program, and delivering outputs for further processing, as shown in figure (4.5)[33]. As mentioned in the previous section, a choice had to be made between “implementing" a simulation program or “ off-the-shelf procuring". Given the scope of this study, which was to perform the simulations

[33] Inertial navigation system by Kjell Magne Fauske (https://texample.net/tikz/examples/inertial-navigation-system/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

and not develop new software, AnyLogic PLE[34] was used. It is a *low-code development platform* (LCDP)[35] offering a substantial increase in software development productivity. Nevertheless, in the case of ServiceSim OR-WPS, especially for advanced functions, *object-oriented programming* (OOP) language such as *Java* had to be used. In section (4.2.5.1), a description of multi-agent classes and agent statecharts, programmed in AnyLogic, is provided.

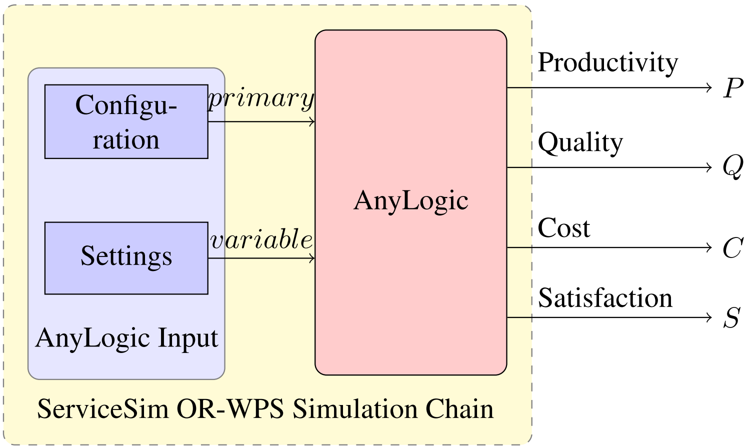


Figure 4.5: Simulation value chain of OR-WPS simulation, from the input of primary configuration and variables to multi-agent simulation to classical and value-based outputs

4.2.5.1 Agent Classes and State Diagrams

OOP uses the concept of *class* to create *objects* state with initial values of their variables, whereas *statecharts* provide behaviours to the agent classes[36]. In figure (4.6), the specifications of Main, OR Coordinator/Scheduler, Anaesthesiology Department, OR Manager and Simulation classes modelled in UML are shown. The concept of statechart (or state diagram) was used in this study to create simulation models. For example, Sobolev et al.[37] used statecharts to simulate patient flow in surgical care. Moreover, a recent survey by Spanoudakis[38] investigated a mapping with

[34] In-depth source: Andrei Borshchev (2013), Big book of simulation modeling - Multimethod modeling with AnyLogic 6 [Bor13]
[35] Source: Alexander Bock et al. (2021), Low-code platform [BF21]
[36] Source: Ibid - Borshchev (2013)
[37] Source: Boris Sobolev et al. (2008), Using the state charts paradigm for simulation of patient flow in surgical care [Sob+08]
[38] Source: Nikolaos Spanoudakis (2021), Engineering multi-agent systems with statecharts [Spa21]

agent-oriented software engineering (AOSE) methods and *engineering multi-agent systems*. They used statecharts to aid the software development process and found that both state charts and AOSE methods are pretty close. For example, by composing a finite number of states for each agent and transitions within, a state diagram can be modelled in UML and implemented in an object-oriented programming language. A generic example of an OR scheduler/coordinator state machine (or state diagram) is illustrated in figure (4.7). Further work by Gunal[39] validated the role of statechart in multi-agent simulation.

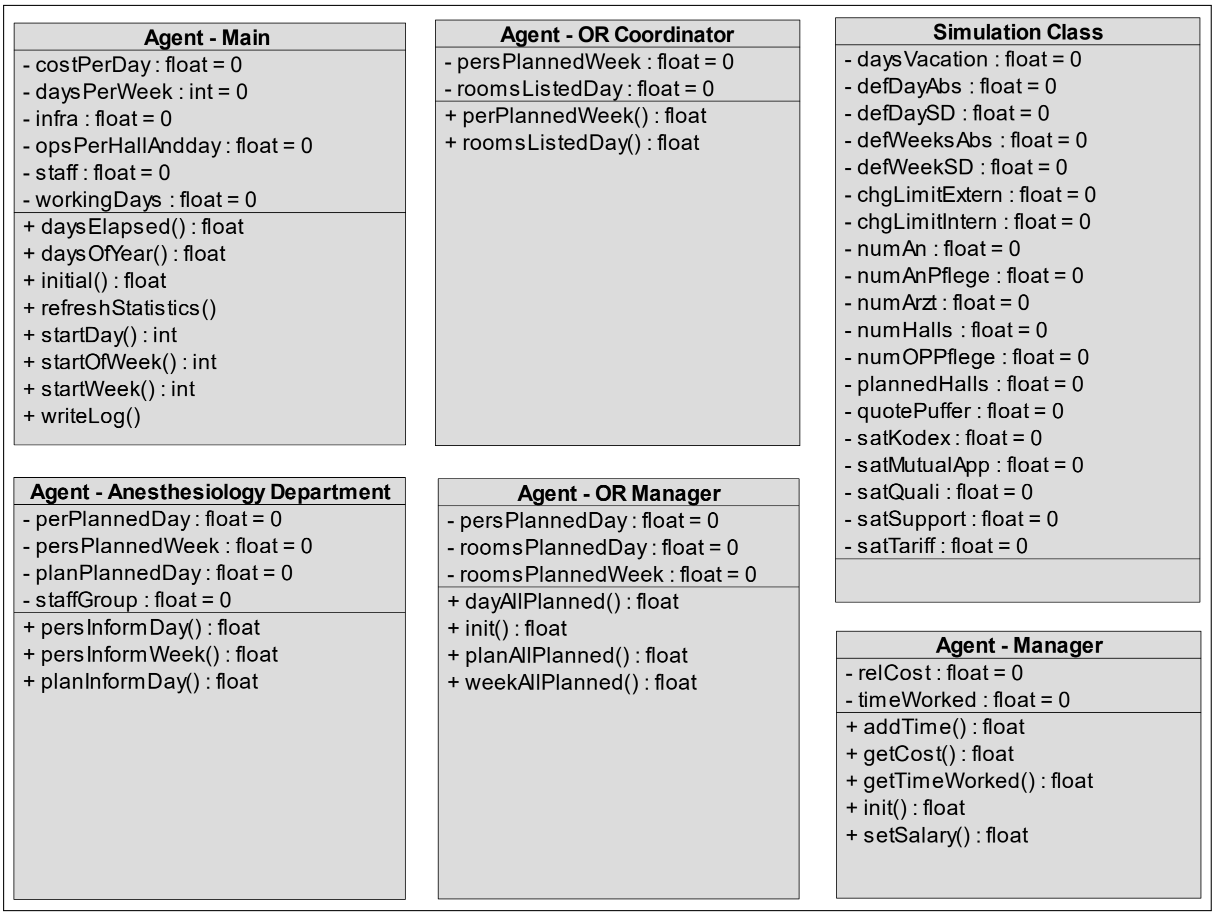


Figure 4.6: Multi-agent class diagrams created with respective attributes and operations modelled in UML language

The behaviour of the OR-WPS agents, as illustrated in figure (4.6) in the form of

[39]Source: Murat Gunal (2012), A guide for building hospital simulation models [Gun12]

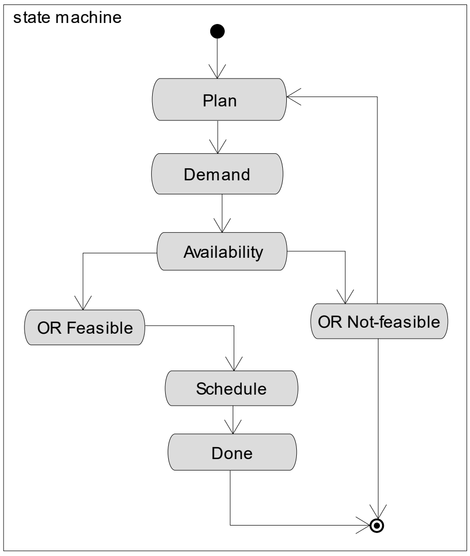


Figure 4.7: Generic state-machine/chart of OR schedulers in UML

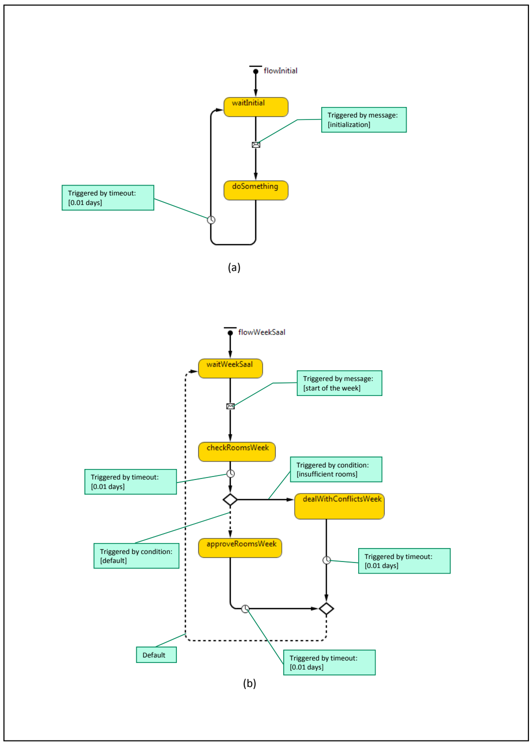
statecharts, is explicitly created based on the OR-WPS process identified in this work and explained in section (4.2.2). The statecharts of the OR manager agent were modelled as shown in figure (4.8). The two sets of statecharts as in sub-figure (i) complement to create a behaviour to initialise the scheduling process of ORs in a week. They initialise and check the OR availability in a week; any resource conflict and OR approval are represented in the form of yellow *curved rectangles* or *states*. The green boxes indicate the *triggering* relationships among the states, which are curved/straight black lines. Similarly, sub-figures (ii) and (iii) created the OR manager's behaviour for scheduling personnel per week and on a day. Figure (4.9) depicts the three separate statecharts, which create for the OR coordinator/scheduler agent's weekly and daily behaviour. The first one (a) is associated with the initialisation, the second (b) gathering information to plan ORs, and the third (c) assigning personnel to this contingent of ORs and the relationships among these via triggering events as aforedescribed. In figure (4.10), two sets of statecharts define the behaviour of an anaesthetist OR scheduler/coordinator agent. The first statechart in sub-figure (i) is initialising the scheduling process and weekly ORs personnel planning. The second in sub-figure (ii) is a set of statechart that defines daily personnel planning/scheduling behaviour. The usual notation with states and relationships among them was based on the business process observed in the hospital, as aforementioned.

4.2.5.2 Simulation Input Variables

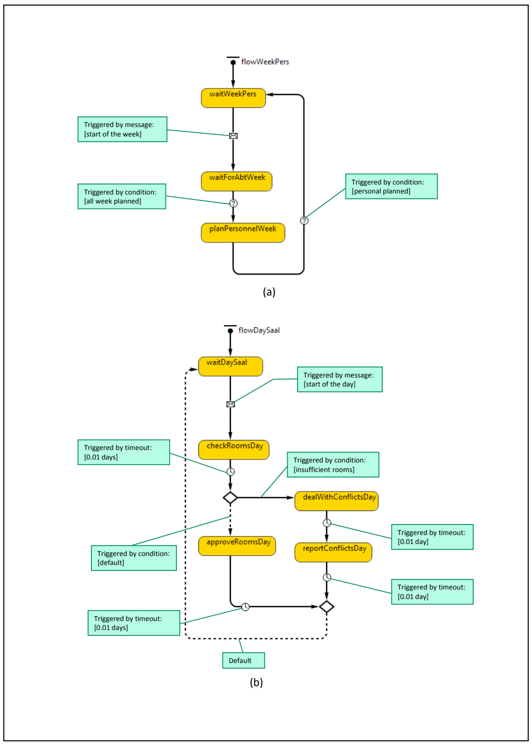
Several inputs are required in a multi-agent simulation of the OR-WPS process. They are grouped into categories to simplify their management for future simulation experiments. The choice as to which data need to be varied and which can remain constant from one experiment is dependent on where support in decision-making to OR manager and OR scheduler/coordinator is needed. The following categories of information[40] must be provided as the inputs.

- General information - Workforce configuration
  - Number of operating rooms
  - Number of surgeons
  - Number of nurses, anaesthesiologists, nurse anaesthetist
  - Simulation time (a few days to an year)
- Value-based information - Workforce satisfaction indicators
  - Qualified personnel
  - Conduct in a team
  - Mutual appreciation
  - Legal working hours
  - Enabling components such as suitable IT application
- Advanced settings
  - Workforce planning
  - Internal workforce limit per day
  - External workforce limit per day
  - Weekly incidents

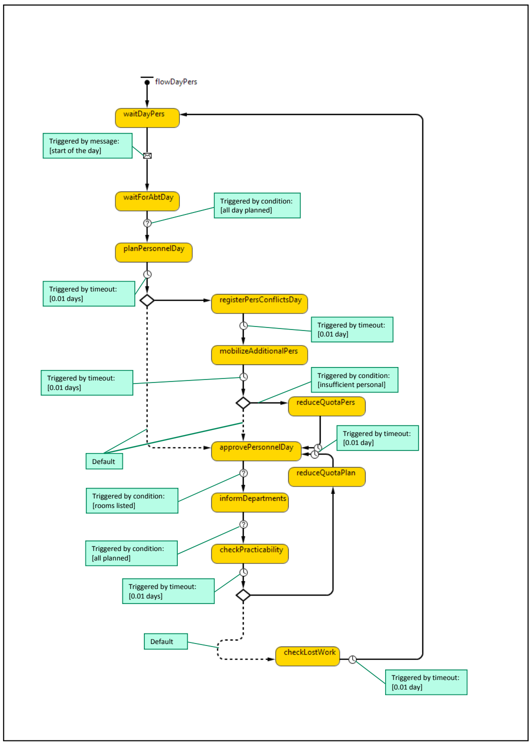
[40] Note: The word *workforce* is used interchangeably with *staff* in this work, as are the terms *value-based* and *value-oriented*.



(i) Initialisation of process of ORs in a week



(ii) Personnel per week and daily ORs



(iii) Personnel per day

Figure 4.8: Statecharts of OR manager agent

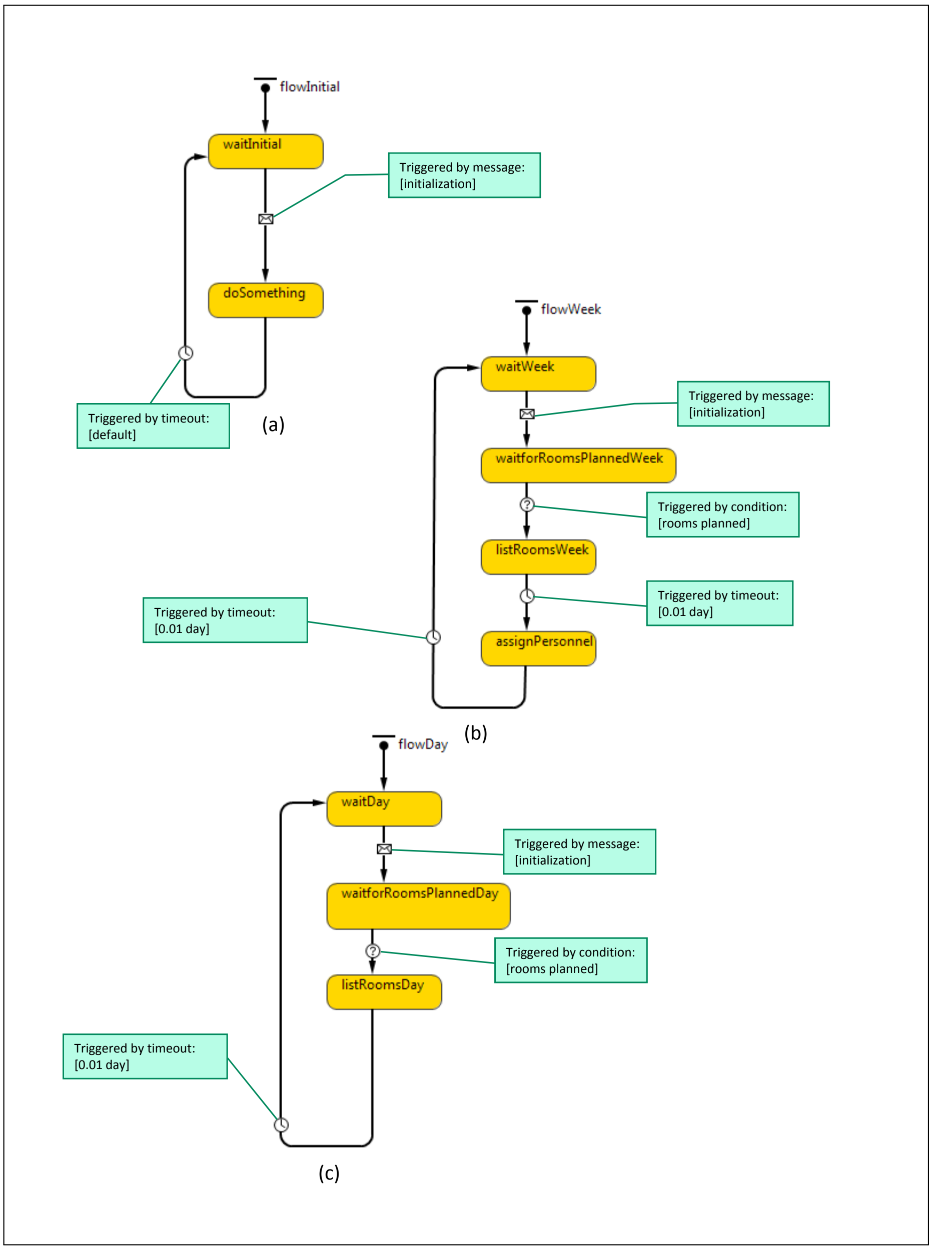
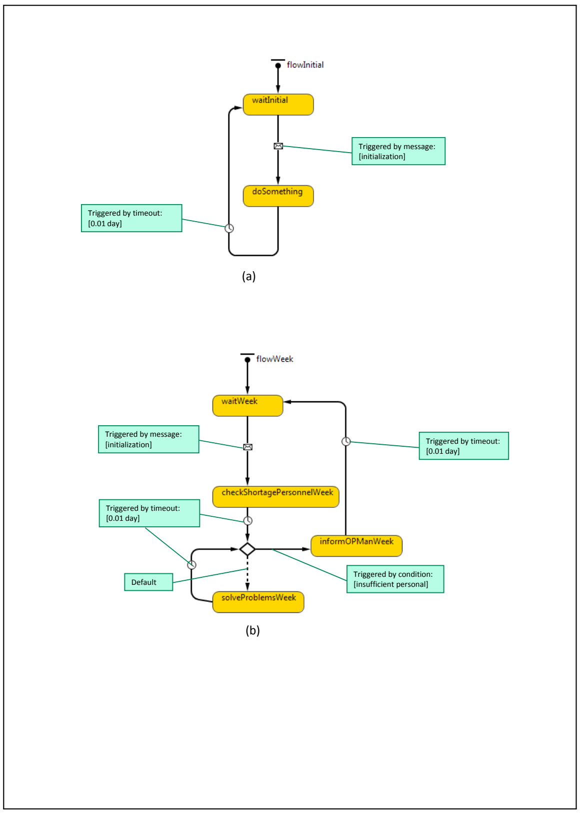
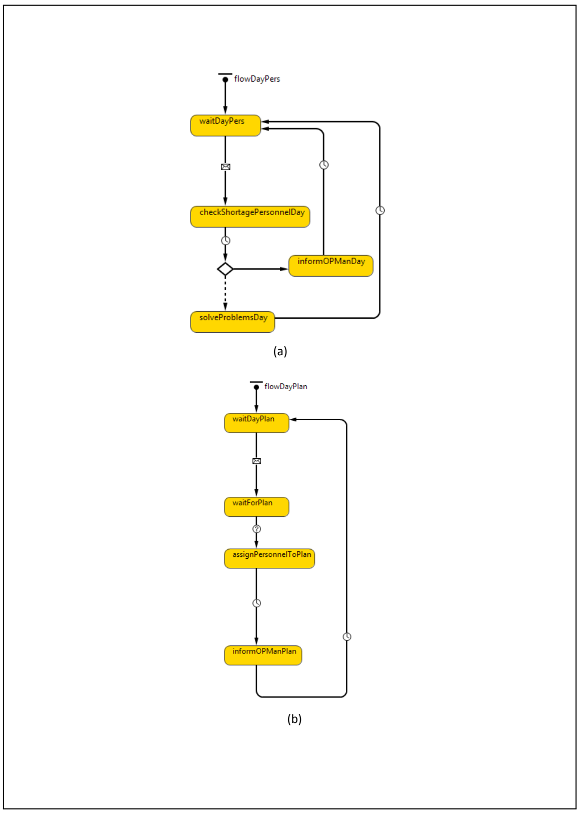


Figure 4.9: Statecharts of OR coordinator while weekly and daily personnel scheduling agent



(i) Initialisation of process and weekly OR personnel planning



(ii) Daily personnel planning

Figure 4.10: Statecharts of anaesthetist scheduler/coordinator agent

☐ Daily incidents

These factors/parameters of simulation can be illustrated as shown in figure (4.11). Upon selecting the aforementioned input data or factors of a simulation experiment and repeating them for many combinations thereof, a portfolio of simulation results would result. These outcomes are classical and value-based KPIs—business process productivity (P), quality (Q), cost (C) and corresponding customer satisfaction (S). Based on the knowledge of current state (or as-is) business processes and input data, if the target future state (or to-be) KPIs for the same business process are known, simulation experiments (or trials on a DT) to achieve them can be performed. Based on the KPIs, one can determine a substantial basis on which a change in business process activities can be asserted physically and implemented. An optimisation/improvement can be achieved; change management in the business process should be the next step to pursue. The real optimisation of the OR-WPS process itself is out of the scope of this work.

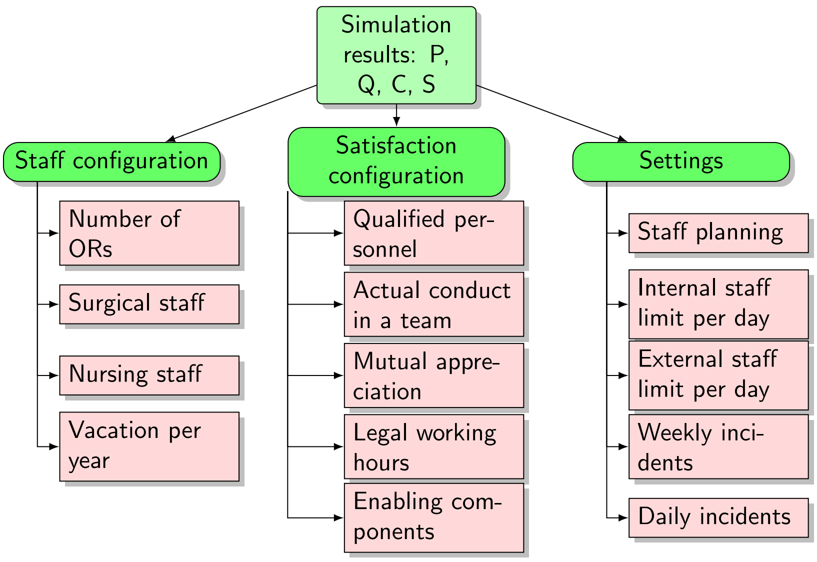


Figure 4.11: Tree of factors for the simulation experiment design for productivity, quality, cost and satisfaction measurements

Although the multitude of inputs can be a challenge, it affords a sufficient degree of freedom (DoF) to the user of ServiceSim OR-WPS as a DSS. The business process does not change overnight, and the activities performed by the process performers cannot be accurately documented. This type of simulation with such input can help guide the healthcare service providers in the investment decisions in workforce hiring, skills development, internal educational offers, and well-thought contracts with external staff suppliers with by-design (or inbuilt) flexibility.

4.2.6 Simulation Output Variables and Dashboard

As regards the *outputs*, the ServiceSim OR-WPS multi-agent simulation was designed to write two types of files while performing simulation experiments, as shown in figure (4.12)[41]. The file “oppep_log.xlog" is a tab-separated values (TSV) file to be analysed using processing software. The second file, “oppep_data.xlog", is also a tab-separated value (TSV) file and used to write output to conclude the simulation run.

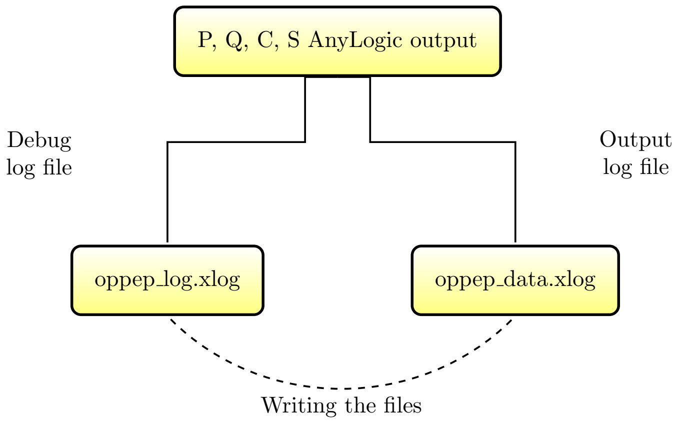


Figure 4.12: Output pre-processing of the simulation runs

The output file contains several variables and the corresponding stored values, and a list of these output variables is shown in table (4.5) for reference. The description of the variables is specific to the ServiceSim OR-WPS only. The use case of ServiceSim OR-WPS, as identified in the relevant section before, is to support the decision-making for specifically direct stakeholders of the process, namely OR manager and OR coordinators/schedulers. Functionally, the users should be able to start and stop the simulation. They should be able to input the variables, run the simulation

[41]Marketing distribution channel by Ashutosh Prasad (https://texample.net/tikz/examples/marketing-distribution-channel/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

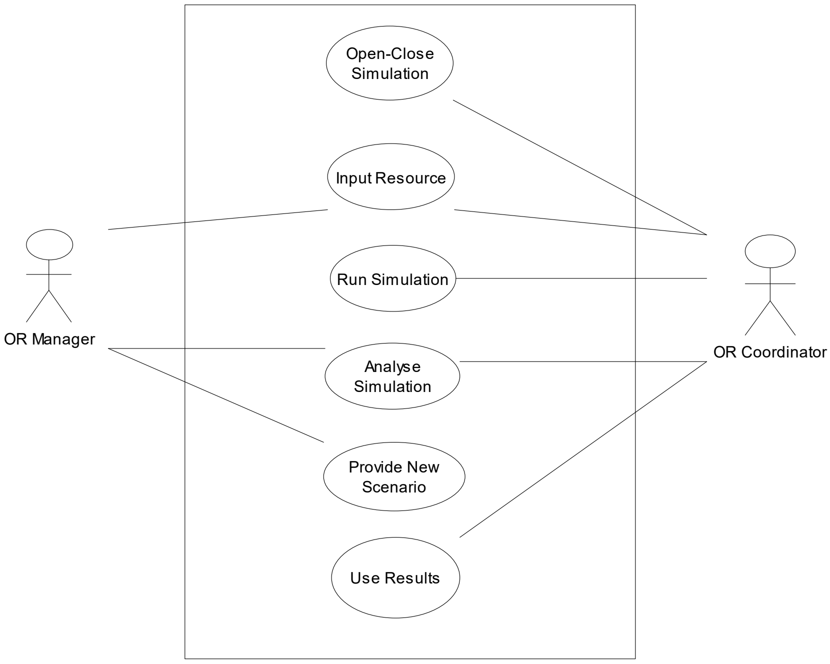


Figure 4.13: Simulation use case diagram in UML for both OR manager and OR coordinator/scheduler of a hospital

with ease and should be able to get the results of the output exported for further processing. The simulation must help improve the future OR scheduling of the workforce. The use cases are as shown in figure (4.13), modelled in UML[42].

In order to design the *user interface* (UI) of the ServiceSim OR-WPS, the findings by Chlebek[43] and by Schmid et al.[44], which provide detailed explanations of the development phases and critical considerations, were employed. AnyLogic offers its own default interface to develop the dashboard prototypes in this work as shown in figures (4.14), (4.15) and (4.16). The design of the performance dashboard for the ServiceSim OR-WPS is fundamentally based on concepts by Eckerson[45] and by Few[46]. To track the progress of the improvement initiatives, the vital process indicators associated with *performance management* must be visualised. Relevant findings by Hans

[42] In-depth source: Kurt Bittner et al. (2003), Use case modeling [BS03]
[43] Source: Paul Chlebek (2011), Praxis der User Interface-Entwicklung [Chl11]
[44] Source: Markus Schmid et al. (2017), Technisches Interface Design [SM17]
[45] Source: Wayne Eckerson (2011), Measuring, monitoring, and managing your business [Eck11]
[46] Source: Stephen Few (2006), Information dashboard design - The effective visual communication of data [Few06]

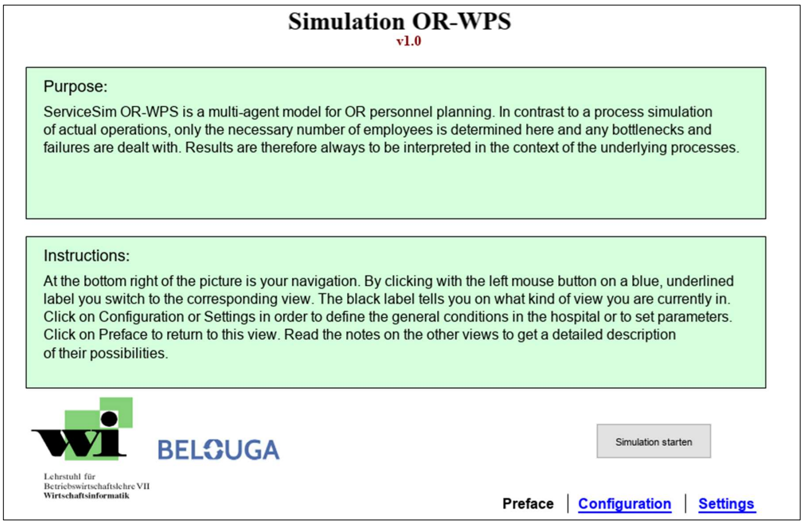


Figure 4.14: Implemented User Interface (UI) of the OR-WPS Lerncockpit dashboard screen

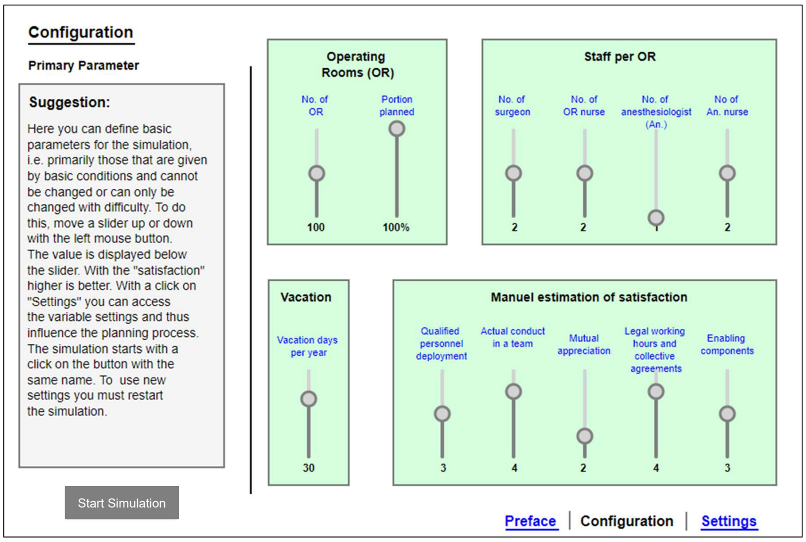


Figure 4.15: Implemented UI for primary parameters of the OR-WPS

et al.[47] helped develop a *serious game*[48] in which the player takes the management team's role in ORs, similarly to the conceptualisation and implementation in this study. The final dashboard based on these inputs is as shown in figure (4.17). It provides a *simulation overview* with the classical and value-based KPIs for the OR-WPS. The long-term vision is to develop the concept continually and, if qualified, deploy it in a

[47] Source: Erwin Hans et al. (2007), Operating room manager game [HN07]
[48] In-depth source: Ralf Dörner et al. (2016), Serious games [Dör+16]

hospital as a serious game for learning purposes. After implementing the ServiceSim OR-WPS in the AnyLogic PLE, the next logical step would be to verify and validate the model, as explained in section (4.2.7).

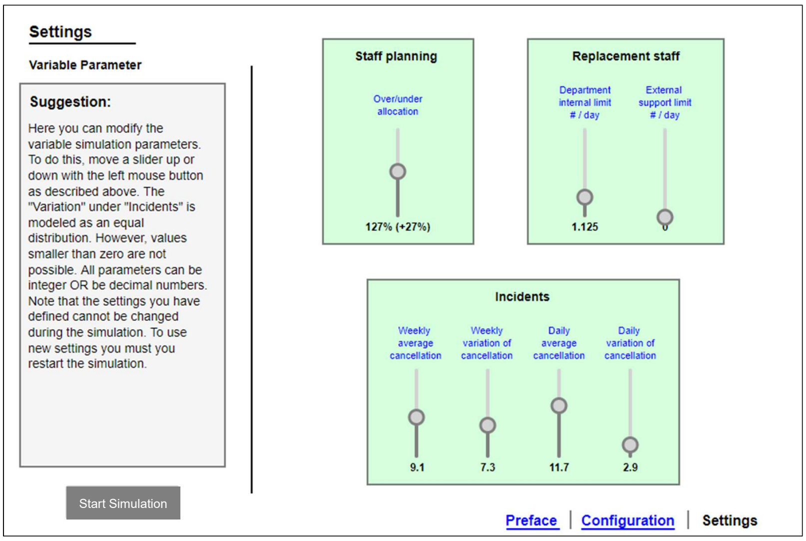


Figure 4.16: Implemented UI for variable parameters of the OR-WPS

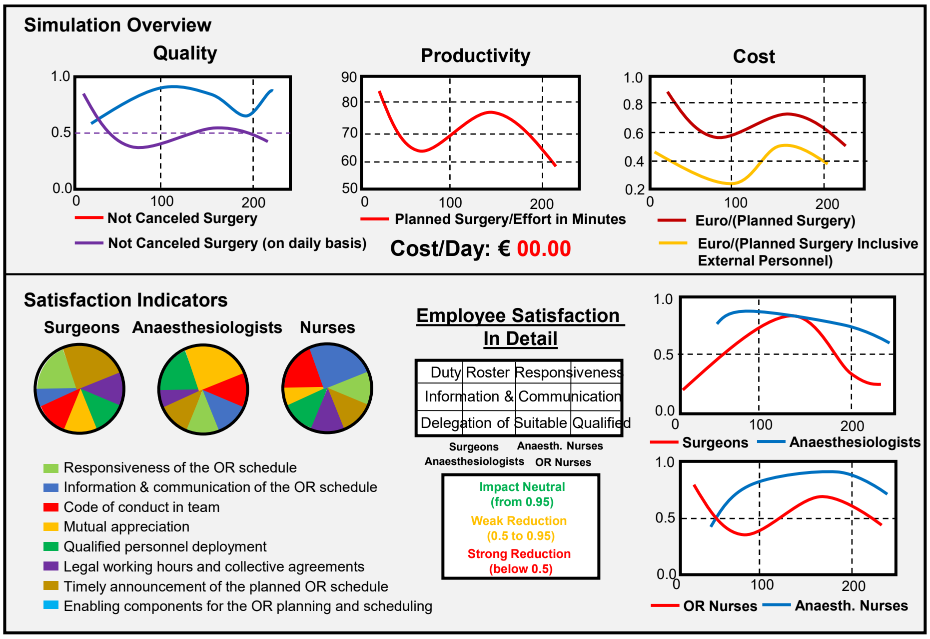


Figure 4.17: Implemented OR-WPS performance dashboard

4.2.7 Simulation Verification and Validation (V&V)

Similar to other simulation studies, ServiceSim OR-WPS should qualify *verification* and *validation* procedures. The definition of *model verification* and *model validation* provided by Sargent[49] can be stated as follows:

Definition 4.20. *Model Verification*

> *"...ensuring that the computer program of the computerised model and its implementation are correct ..." [Sar09, p. 162]*

Definition 4.21. *Model Validation*

> *"...substantiation that a computerised model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model ..." [Sar09, p. 162]*

To verify the OR-WPS simulation model, the primary step was to ensure that the conceptual model's implementation was correct. The various techniques used to verify the model were as follows:

(a) a formal check of the logic of heuristics and algorithms;

(b) informal check of the agent classes and functions;

(c) static check of visual code in AnyLogic; and

(d) dynamic check of ServiceSim OR-WPS during execution.

As shown in figure (4.18)[50], in the case of validation of the simulation models, the work by Murray-Smith[51] and the works edited by Beisbart et al.[52] provide the main guidance. Sargent[53] has described four different approaches to check the model's validity. The ServiceSim OR-WPS must at least qualify the two levels of validation:

[49] Source: Robert Sargent (2009), Verification and validation of simulation models [Sar09]

[50] Work breakdown structures aka WBS diagrams by Rasmus Pank Roulund (https://texample.net/tikz/examples/borrowers-and-lenders/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

[51] Source: D. J. Murray-Smith (2015), Testing and validation of computer simulation models [MS15]

[52] Source: Claus Beisbart et al. (2019), Computer simulation validation - fundamental concepts, methodological frameworks, and philosophical perspective ([BS19])

[53] Source: Ibid - Sargent (2009)

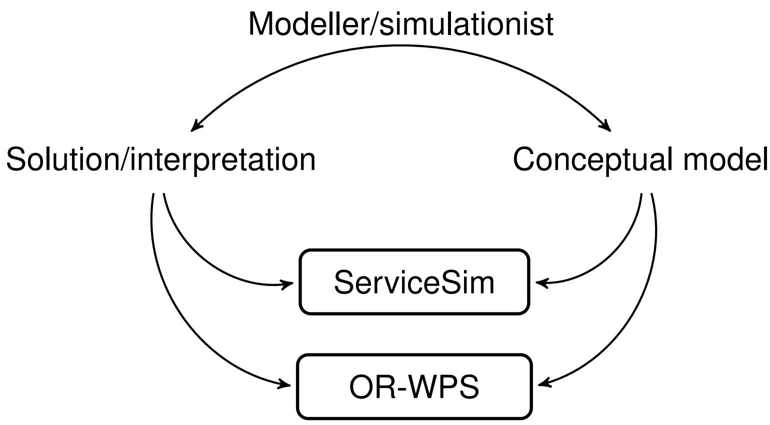


Figure 4.18: In the context of this work, validation is alignment between OR-WPS (real-world problem) with both conceptual model and solution/interpretation. In contrast, both ServiceSim (simulation model) and conceptual model are verified. The modeller/simulationist directs these alignments.

qualitative and *quantitative*. In qualitative validation, the model is supposed to reproduce the logical results and correspond to the simulation problem at hand. A case study is a valid instrument to validate a model's results with the subject-matter experts (SMEs). The case study is described as follows.

Case Study—Background Information

The (hypothetical) medical-care hospital considered in this case study has had problems with the organisation and operations of OR-WPS for a long time. This process area consists of a workforce scheduling for the preoperative rooms, a few of operating rooms, the postoperative rooms. It is observed that the waiting times for patients are more extended than before. The service-related dissatisfaction of the patients also affects the medical workforce/staff. The OR manager agrees that this situation is no longer acceptable long term and that a solution must be found. Since OR-WPS is an enabling function, the processes must be well structured to motivate and satisfy the workforce/staff, and patients receive a good service. Ms Mueller, an OR coordinator/scheduler of the service, is instructed by the OR management to improve the operating room workforce scheduling process. However, before Ms Mueller can find a solution, she decides to analyse the areas in which problems are occurring more frequently. She observes day-to-day operations (job-shadowing) closely in the days that follow and is repeatedly confronted with various problems. These problems can be grouped into three problem areas. First, the service level of the OR-WPS is considered too low. Secondly, long working hours in the functional units such as nurse and nurse anaesthetists occur repeatedly. Finally, the OR management considers the overall costs of the OR-WPS service to be excessively high.

Now that Ms Mueller has completed the analysis, a solution must be developed to implement the improvement measures. For this purpose, the hospital's CIO and COO have agreed to use the Lerncockpit to simulate the processes of the OR-WPS area. After a short introduction, Ms Mueller can operate the ServiceSim OR-WPS multi-agent simulation software and learns what she needs to change to bring optimised results in terms of productivity, quality, cost, and customer satisfaction of the OR-WPS service. She can observe the direct effects on productivity, quality, cost, and customer satisfaction by changing the input parameters and performing several simulation experiments. Owing to the high level of complexity involved, the aim is to address the aforedescribed background information and perform validation using different cases as described below:

(a) **Case 1: Yearly planning for the OR**
Every working day, from morning till evening, more than ten patients get surgeries in the ORs of the Medical-Care hospital. Each operating room needs at least one nursing and nurse anaesthetist each. The anaesthesiologist must be available for each ORs. Considering the legally admissible vacation for the workforce, the OR manager would like to know if the scheduling of her personnel for ORs would work. She delegates this task to Ms Mueller to perform several experiments with several ORs to check the feasibility of the (historical) OR schedule with an increase in capacity for the coming year. These results could be used for the workforce hiring strategy of the hospital.

(b) **Case 2: Keeping as much high-level satisfaction among the workforce**
Only fifteen patients need to be treated in the morning OR. The OR manager would like to know if it is costly to run the OR when the help of an external workforce is used to avoid any abrupt absence of an internal workforce while keeping customer-satisfaction levels among internals as high as possible. An easy staff

scheduling can be guaranteed, but the manager expects that it will be costlier to the ORs if this continues for a longer duration, such as a few weeks or even months. He would like to use the results to justify the new hiring strategy of the Medical-Care hospital.

(c) **Case 3: Scheduling with more demand than supply**
Tomorrow in the afternoon, fifteen patients must be treated in the orthopaedics ORs. Planned OR service consists of a nurse, nurse anaesthetists and anaesthesiologists for each of the fifteen ORs. On the day of the surgeries, a few colleagues were ill and were supposed to be on duty. External help can act as a buffer for the next day. How do the simulation results look in terms of productivity, quality, customer satisfaction and high cost, as external help is costlier than internal one? Do the results agree with the real-life situation?

The cases described above were used to validate the ServiceSim OR-WPS simulation. As described in section (5.3), the model works within the acceptable ranges of inputs and acceptable values of outputs. It has been established that the challenges faced by modellers in verification and validation are not trivial[54]. The following conclusions could be drawn from the verification and validation of the ServiceSim OR-WPS:

- The simulation model of OR-WPS is verified. Within the range of valid inputs, the software program produces valid outputs. No errors during the execution were found to be present.
- The model qualified the validation with a few business process stakeholders in one German and one American hospital.

Execution of V&V provided an opportunity to examine the topic of *trust* in the model developed in this study. Harper et al.[55] reported that trust in simulation studies is still open to further exploration and how trust can be quantified/measured. Lack of input data, insufficient simulation in terms of scenarios, or lack of experience in using the simulation outputs can influence the trust in this model. It is not yet foreseen

[54] Source: Dale Pace (2004), Modeling and simulation verification and validation challenges [Pac04]
[55] Source: Alison Harper et al. (2021) Facets of trust in simulation studies [HMY21]

that, as a PoC, the ServiceSim OR-WPS can guide the OR coordinator/scheduler or manager in all sets of possible real-world scenarios. Particularly in the healthcare service domain, it is challenging for the validated model to quickly gain acceptance, as healthcare concerns patients' lives and fulfils all the characteristics of being an HRO. In chapter (6), the focus is on the EA method for OR-WPS, precisely aligning with the hospital's vision, technology trends, architecture principles, and high-level requirements, followed by physical, information, and project architecture.

Classification	*Question*	*Follow − up*
Strategic	How is a hospital's competitive positioning in the healthcare market?	What provides the hospital with a competitive advantage over the competitors? Is it cost-structure, or skills and reputation of hospital staff?
		Does the hospital have a budget and negotiating power with third party payers to increase its revenue?
	How is the hospital's network promotion, i.e. the activities that will hire the medical professional with the best skills and correct numbers?	What is the current state of network infrastructure, i.e. how is the investment in the information technology infrastructure?
		What kinds of services are provided by the hospital? Is its strategy stressing low cost or high quality, range of service provision, or does it focus on specific customers, the service to the customer, or using technology?
Tactical	What is the hospital's contingency planning for nursing and physicians?	Which information does the workforce receive from various departments? How is the communication of the final contingency plan to the workforce?
	How does the hospital deal with staff vacation planning?	Does the hospital have established contracts with external staffing agencies to provide a buffer when extra help in the OR is needed?
		Which planning activities take the most time? How much time do they consume out of total working hours?

Table 4.3: Interview—discover the OR staff scheduling supporting process, stakeholder communication and coordination (based on one of the outcomes of BELOUGA project)

Variable	*Description*
No. of ORs	Determine the various (workforce) organisational groups (nursing, anaesthesia nurse, OR coordinator/scheduler)
Planned ORs	Assess the total cost of each organisational group
Resources per OR	Asses the availability of each organisational group (e.g. working time, deduct the vacation, meeting and/or training hours)
Paid Vacation	Determine the per-unit cost of each organisational group by dividing the total cost of the organisational group by the availability
Resource Buffer	Determine the time taken for each event in the computer simulation
Weekly Incidents	Multiply the per-unit cost of each organisational group by the simulation real-time for the event
Weekly variation	Determine the time taken for each event in the computer simulation
Daily Incidents	Multiply the per-unit cost of each organisational group by the simulation real-time for the event
Daily Variation	Determine the time taken for each event in the computer simulation
Internal Limit	Multiply the per unit-cost of each organisational group by the simulation real-time for the event
External Limit	Determine the time taken for each event in the computer simulation

Table 4.4: Steps to determine the cost drivers and time duration of service

Variable	*Description*
days	Simulation day (time)
def	Number of rooms not available each week
defC	Counts of those incidences
defEff	Help variable for the adequate number of days compared to 'days' variable
#week	Number of ORs before the week starts
#day	Number of ORs after day one
STAFF	Help variable to indicate starting of the new column
TmpPers	External temporary staff - global variable
TmpPerC	A counter on how often the shortage of staff occurs
DOCS	Demand - how many surgeons are required for all the ORs
#tot	Surgeons available = DOCS + buffer - on vacation
#avail	Additional surgeons available due to the effect of earlier vacation
Wprob	Number of workforce missing weekly (for the whole week)
#week	(#avail - Wprob) for each department
WeekAddC	Counts if additional staff is required this week - remains the same for the whole week
Dprob	Effective shortage on the daily basis
#day	Number of people available for that particular day, i.e. (demand - Dprob)
DayAddC	Counter of events when Dprob is non-zero
DVacAdd	Total number of vacation days to be added
DLost	Counter of events when Dprob is non-zero
LostC	The Counter on DLost occurrence
evRefreshStatistics	= 1.001 × day. This variable is used to write the statistics after each day using an event in the function "refreshStatistics".
LostC	The Counter on DLost occurrence

Table 4.5: The variables listed store the output to the oppep_log.xlog file for further processing

4.3 Quantitative Study in OR-WPS Process Area

In order to determine the *statistical distribution* that fits the random sample data for the OR-WPS process, the *work-sampling* method as described in chapter (2) in section (2.2.5.2) can be employed. The aim was to determine the most suitable distribution that can be used to describe the data and create *random numbers* to run a stochastic computer simulation. The idea behind randomness is to handle risk and uncertainty with which the random observations would influence the simulation results and thus reach an informed and reliable decision on which process improvements to undertake. Ishimoto et al.[56] reported the combination of work sampling and computer simulation for optimised assignment of personnel in the pharmacy domain. The output of sampling was used as an input in a computer simulation. The procedure of determining the appropriate probability distribution is known as *distribution fitting* and is illustrated in figure (4.19).

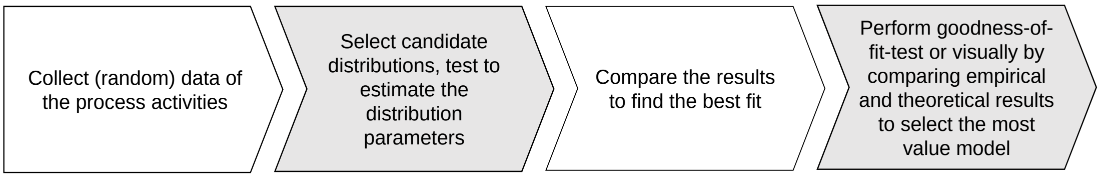


Figure 4.19: Procedure from random data till finding the best model for input in the computer simulation (own diagram)

The premise of a work-sampling study is an inquiry stating a (central) RQ and associated sub-questions[57]. The RQ herein demands the examination of the OR-WPS process area during job-shadowing.

> *(Central) RQ3: Which approach would be suitable to create the statistical models of simulation input within a typical hospital, and how can it contribute to addressing the current research gaps in input modelling?*

A few sub-questions followed the central RQ3:

[56] Source: K. Ishimoto et al. (1990), Computer simulation of optimum personnel assignment in hospital pharmacy using a work-sampling method [Ish+90]

[57] Source: John Creswell (2014), Research design - Qualitative, quantitative, and mixed methods approaches [Cre14]

(Sub) RQ: How can one systematically conduct the investigation and collect the work sampling data about the intra-day running of the OR-WPS process?

(Sub) RQ: How can one create mutually exclusive and collectively exhaustive (MECE) categories of activities conducted by schedulers to test their validity?

(Sub) RQ: How much work sampling data, in terms of days of observation, is needed so that results could tell something about the population?

(Sub) RQ: How could the results of work sampling be used in future ServiceSim OR-WPS computer simulation as well in artificial intelligence such as machine learning?

In the following subsection, an attempt to answer the central and sub RQs is described.

4.3.1 Method

The objective of the work sampling is to determine the time taken by various OR schedulers each day on activities that are related or unrelated to scheduling. For example, these activities could include writing on the OR board, communicating relevant information on the phone, or even actively participating in medical service in response to the sudden illness of the scheduled staff. The data collection exercise has two main uses: determination of approximation time spent on the activities listed in the process maps to perform the simulation and prioritisation of the activity improvement based on the analysis outcome. In order to conduct the quantitative work sampling analysis, the starting point was job-shadowing in the UMHS. In the UMHS field study, several individual stakeholders' OR-WPS processes were separately followed throughout a particular work shift and observed[58]. These shadowings were documentation in the form of histograms of the *observations* in the predefined categories. The next step was to evaluate the collected histograms based on the theory of work sampling. The job-shadowing was not recorded; therefore, auditory data material was not available.

[58]Note: For personal data protection, the names were anonymised.

Any observation obtained during the shadowing was transcribed in British English, and the aim was to reproduce any actual conversation. In order to determine the *sufficient* number of observations that must be made to be *confident* in the activity time results produced, one needs to determine the sample size of the observation be made. The *relative accuracy* of the results per industrial standard can be established to be ±10%, ±5% or ±1% before the observation began[59]. The mathematical equation, according to Aft[60], is defined in equation (4.22).

$$\boxed{n = \frac{Z^2(1-P)}{(P)(A^2)}} \tag{4.22}$$

where:

n = Total sample size
Z = Confidence level
P = A preliminary estimate of the % of time spent performing a particular activity
A = Desired accuracy

By setting the requirements such as confidence level Z = 2.575[61] or 99%, P = 15% estimate of time spent on significant activity in OR-WPS related scheduling and A = 10% accuracy, the calculated sample size is n = 3757. If the confidence level is Z = 1.96 or 95% and other variables are the same, the minimum sample size should be n = 2177. The work sampling requires a stream of pseudorandom numbers as input. Therefore, a freely available random time generator[62], which is an excellent random number service that generates randomness via atmospheric noise, was used in this study. This random number generator passes the test of the US National Institute of Standards and Technology (NIST). The only limitation of this generator is that it could only produce 100 random clock times simultaneously. Therefore, the sample set, which should contain as many samples as possible, with 400 clock times in total was produced using the generator four times, as shown in figure (4.6). Owing to the cost incurred in performing this study, the investigation of the ORs scheduler was set for five days. It was performed from Monday to Friday, from 6:30 till 14:30, starting in the

[59] Note: The number of observations required increased tremendously with increased demand for accuracy. Absolute accuracy has time (min or h) as its unit.
[60] Source: Lawrence Aft (2000), Work measurement and methods improvement [Aft00]
[61] Note: For Z values, see also Aft [Aft00, p. 324])
[62] Note: Random clock time generator—https://www.random.org/clock-times/

second week of September 2015. It was expected that the scheduler would perform almost all the activities in this time frame without any holidays or office breaks. The job classification for the study was the different roles that scheduled the workforce for the ORs. Various activities performed by the OR board runner at the University Hospital were identified during the observation over two days and yielded a list of activities and their categorisation. The observed roles were informed, and the approval from the institutional review board (IRB) was obtained. The results of the work sampling study are presented in section (5.4) of chapter (5).

Day 8	Day 8	Day 8	Day 8	Day 8	Day 8	Day 8	Day 8	Day 8	Day 8	Day 8	Day 8
06:32	09:33	12:49	06:32	09:54	12:51	06:39	09:55	12:45	06:37	10:04	13:09
06:34	09:35	12:51	06:37	10:02	13:05	06:49	09:59	13:10	06:38	10:15	13:12
06:40	09:37	12:57	06:38	10:03	13:09	06:50	10:03	13:11	06:50	10:24	13:13
06:44	09:44	13:03	06:41	10:04	13:10	06:52	10:04	13:13	06:52	10:26	13:15
06:45	09:48	13:20	06:44	10:08	13:23	06:56	10:07	13:20	07:11	10:32	13:21
06:50	09:50	13:23	06:45	10:11	13:26	07:02	10:11	13:23	07:19	10:34	13:24
06:51	09:52	13:24	06:53	10:12	13:27	07:07	10:13	13:26	07:21	10:40	13:27
06:52	09:54	13:26	07:17	10:13	13:29	07:12	10:15	13:32	07:22	10:41	13:28
06:53	10:05	13:31	07:20	10:15	13:32	07:13	10:24	13:34	07:30	10:45	13:33
06:59	10:08	13:35	07:29	10:20	13:40	07:24	10:30	13:38	07:31	10:46	13:40
07:00	10:10	13:38	07:38	10:28	13:42	07:25	10:31	13:44	07:37	10:47	13:41
07:03	10:23	13:44	07:41	10:37	13:45	07:36	10:32	13:48	07:43	10:53	13:50
07:08	10:29	13:46	07:47	10:40	13:46	07:39	10:35	13:51	07:44	10:54	13:51
07:16	10:39	13:51	07:54	10:43	13:49	07:44	10:39	14:06	07:49	10:55	13:54
07:19	10:40	14:10	08:12	10:45	13:50	07:49	10:47	14:08	07:51	10:57	14:00
07:20	10:45	14:14	08:17	10:47	13:52	07:53	10:58	14:10	07:58	10:59	14:05
07:35	10:46	14:16	08:19	10:49	13:54	07:56	10:59	14:11	08:00	11:02	14:10
07:36	10:47	14:17	08:22	10:50	13:55	07:58	11:01	14:14	08:13	11:03	14:12
07:41	10:50	14:19	08:24	10:54	14:02	08:02	11:08	14:15	08:22	11:09	14:22
07:45	10:55	14:20	08:27	11:07	14:07	08:03	11:09	14:18	08:26	11:20	14:24
07:48	11:02		08:28	11:11		08:04	11:10		08:31	11:28	
07:58	11:08		08:30	11:13		08:08	11:27		08:35	11:35	
08:00	11:12		08:43	11:18		08:18	11:31		08:39	11:51	
08:06	11:13		08:46	11:20		08:21	11:34		08:43	11:54	
08:10	11:29		08:47	11:24		08:25	11:35		08:51	12:08	
08:18	11:44		08:49	11:25		08:37	11:38		08:53	12:09	
08:22	11:46		08:51	11:29		08:38	11:39		08:59	12:12	
08:34	11:58		08:53	11:30		08:40	11:44		09:00	12:13	
08:46	12:00		08:54	11:34		08:42	11:53		09:03	12:14	
08:53	12:01		08:57	11:39		08:46	11:54		09:05	12:25	
08:55	12:03		09:03	11:46		08:51	12:01		09:16	12:28	
09:05	12:09		09:05	11:48		09:10	12:05		09:18	12:36	
09:07	12:16		09:15	11:59		09:13	12:06		09:25	12:43	
09:11	12:20		09:21	12:09		09:17	12:17		09:30	12:47	
09:12	12:22		09:23	12:28		09:26	12:24		09:40	12:49	
09:14	12:25		09:27	12:29		09:27	12:26		09:41	12:51	
09:15	12:35		09:30	12:32		09:32	12:27		09:43	12:53	
09:23	12:39		09:35	12:34		09:37	12:28		09:47	12:57	
09:27	12:43		09:40	12:37		09:42	12:41		09:59	12:58	
09:31	12:46		09:48	12:45		09:48	12:44		10:02	13:00	

Table 4.6: A sample of 400 random times for a morning shift from 6:30 till 14:30 was used for observation

4.4 Survey Based International Comparison in OR-WPS

In the BELOUGA project[63,64], this study identified the value for the customer in the OR-WPS enabling process of the hospitals. The *value-for-the-customer* can be determined in terms of the *customer-perceived value*. Based on the analysis, the following roles in the OR-WPS process were determined as shown in figure (4.20):

(a) *Customer/recipient of the service*: Surgeon, Anaesthesiologist and Nursing staff

(b) *Provider of the service*: Management of speciality departments responsible for staff planning/scheduling, OR management and OR coordinator

(c) *Sponsor of the service*: Hospital management

(d) *Payer of the service*: Hospital (central) administration

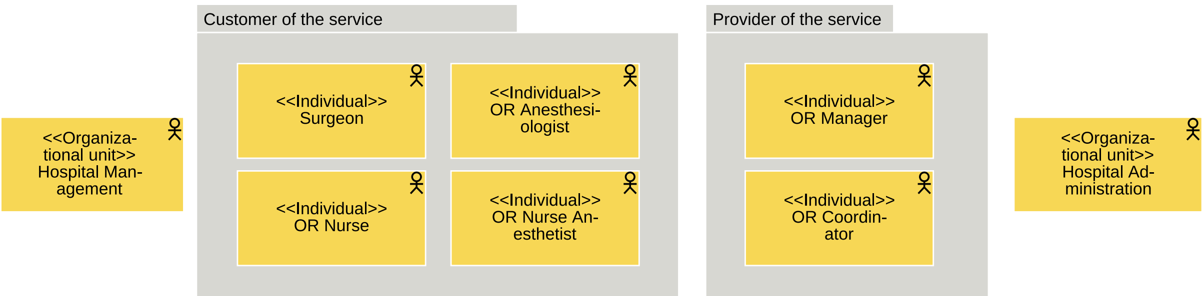


Figure 4.20: The various roles of the OR-WPS such as customer, provider, sponsor and payer (based on one of the outcomes of BELOUGA project) in ArchiMate® modelling language

The identification of the different roles and the value perceived by these roles about the OR-WPS was established empirically using the Identification of Service Gaps (ISL) approach published by Woratscheck et al.[65]. The focus of the BELOUGA was on the customer and provider of the service. In contrast, the payer and sponsor of

[63] Source: Herbert Woratscheck et al. (2015), Wertschöpfungsorientiertes Benchmarking [Wor+15b]

[64] Note: Algorithm to perform statistics and analysis supported by Department for Marketing and Service Management, University of Bayreuth, Germany.

[65] Source: Herbert Woratscheck et al. (2007), Identifikation von Servicelücken bei Dienstleistungsunternehmen [WHP07]

the service were out of scope in the following quantitative study. The value of the service is measured based on both the value perception of the customer and the service provider. After research scoping, the expert interviews of the (process) roles were conducted using guideline-based interview questions to find out their subjective perception, followed by the adjustment of interviews based on feedback received from the interviewee. A (modular) questionnaire regarding the responsibility of the interviewee in the OR-WPS enabling process, further communication among roles and the level of cooperation during the process execution were focused and inquired. The insights gained in the BELOUGA on the OR-WPS, if appropriately customised, adjusted, and tested to another (national/international) healthcare system that is culturally as well as economically different and geographically separated, could be interesting from the perspective of benchmarking. Therefore, BELOUGA was extended to BELOUGA-M-project, focusing on a major hospital in Missouri (USA) with the following central RQ:

> *(Central) RQ4: Which are the essential differences in the results between the surveys conducted among OR-WPS stakeholders at the hospitals in Germany and the USA?*

The contrast between the American and German healthcare systems has been substantially researched. Focusing on the findings of healthcare-related "job satisfaction", the relevant prior studies and their findings on this matter are summarised as follows:

(a) Janus et al.[66] studied work-related monetary and non-monetary factors and their influence on job satisfaction. They focused on addressing the question whether the American physicians are more satisfied than others. Reimer et al.[67], in contrast, performed a study on the suicidal tendency of female and male physicians. Siegrist et al.[68] examined work-related stress in the three respective health care systems. These studies and their main results can be summarised as follows:

[66] Source: K. Janus et al. (2009), Sind amerikanische Arzte zufriedener? - Ergebnisse einer internationalen Studie unter Arzten an Universitätskliniken [Jan+09]

[67] Source: Christian Reimer et al. (2005), Suizidalität bei Arztinnen und Arzten [RTJ05]

[68] Source: Johannes Siegrist et al. (2010), Work stress of primary care physicians in the US, UK and German health care systems [Sie+10]

- On average, German physicians are less satisfied than their American counterparts[69,70].
- The reason for the lower satisfaction of German physicians cannot be explained by the business-cultural context alone and that there are other reasons[71,72].
- The factors that influence overall satisfaction are *autonomy* in taking decisions and appreciation and recognition and *collegial relationships* and *continuing education/training*, and use of unique technologies or *time-referenced workload*[73].

(b) Factors influencing overall job satisfaction such as *autonomy* in taking decisions or *time-referenced* workload play an essential role in both Germany and the United States. The OR-WPS enabling process partly steers them.

On the basis of the literature, it can be concluded that no extant study focused on enabling processes such as OR-WPS and measured the value-based indicators of its roles (at the time of writing this thesis). A set of arguments supporting this study, which compared two sets of questionnaire outcomes, are as follows:

(a) From a research perspective, it is worthwhile to examine the cause of any dominant value dimension that contributes to an (overall) job-satisfaction.

(b) Value dimensions in BELOUGA are relevant for OR-WPS and other planning/scheduling process areas. This can be elaborated as follows:

- Common factors or dimensions (for instance, the responsiveness of the OR schedule or timely announcement of the planned schedule) might play a significant role in other types of scheduling, especially in those wherein humans are the subject.
- Similar to OR-WPS, which is a cost-intensive as well as a highly profitable process area for healthcare providers and has the most important role in the profit margins, other domains also have similar process areas.

[69] Source: Ibid - Janus et al. (2009)
[70] Source: Ibid - Reimer et al. (2005)
[71] Source: Ibid - Janus et al. (2009)
[72] Source: Ibid - Siegrist et al. (2010)
[73] Source: Ibid - Janus et al. (2009)

(c) Considering the *business* and *cultural* differences between Germany and the US on the level of the OR-WPS process area as described in section (4.2.2), the following aspects could be worth investigating:

- If there exists a difference in the business culture, where are the opportunities, threats, risks and means of exploitation as well mitigation?
- What are the assumptions about rules and norms adopted despite business-cultural differences?
- Can the knowledge gain concerning a healthcare system focusing on OR-WPS in one country be transferred to another? Would this have an effect, or would it be easy in spite of the fact that the perception of specific value dimensions on the overall satisfaction is different?

4.4.1 Method

As the (original) survey (modelled as an *assessment*) was designed for the German hospitals for OR-WPS (modelled as a business *requirement* to research), which investigated in different dimensions (modelled as customer-related *outcomes*) as shown in figure (4.21), it needed a validation with the American counterparts for the relevance of the questions.

A total of eight (qualitative) interviews were conducted, for instance, with Head and Neck Surgical Oncology, Medical Director—ORs; Director, Surgery Services; a former Surgeon; Manager, Surgical Services; Business Technology Analyst; Manager, Surgical Materials and Sterile Processing Department; OR Board Runner; and Director, Payer Strategy at a hospital in Missouri (USA). The validation was conducted on the qualitative content analysis composed of 26 value characteristics and their relevance in the American context focusing on the following aspects:

(a) Collaboration

- Cooperative behaviour
- Appreciation
- Team composition

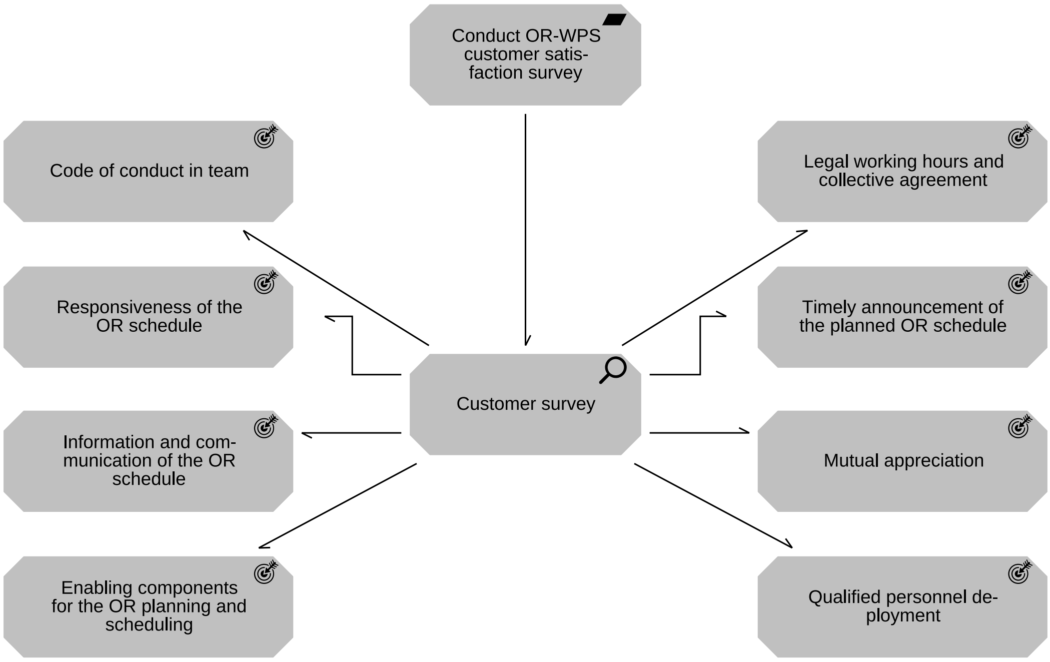


Figure 4.21: Overview of a survey of measuring to eight value dimensions (which are herein referred to as factors) of the OR-WPS process (based on one of the outcomes of BELOUGA project) modelled in ArchiMate® language

(b) Communication

- Information sharing
- Short-term changes
- Agreement

(c) Planning process

- Organisation
- Announcement of planning steps
- Compatibility with private life
- Compliance with rules
- Quality
- Dealing with emergencies
- Coordination of scheduling

(d) Participation

- Consideration of requests
- Autonomy

(e) Fairness

- Balance and equitable distribution of services
- Compensatory time off
- Varied scheduling
- Transparency

(f) Human resources

- Flexibility
- Staffing
- Qualification
- Training and development

(g) Infrastructure

- Working time legal and collective agreement requirements
- Information technology application for support
- Material resources

On the basis of the aforedescribed facts, the OR-WPS significantly contributes to overall work-related satisfaction owing to its complex character involving heterogeneous skilled personnel, high turnover for hospital revenue, and its place at the heart of hospital management. In the mid-year 2016, a survey similar to project BELOUGA was conducted at UMHS. The survey was translated from German to English with minor changes according to the healthcare system in Missouri (USA). Table (4.7) provides the scope regarding the number of participants in the survey with their profession at UMHS.

According to Weinbroum et al.[74] and Janus et al.[75], the healthcare systems, specifically in the operational process area of operating room planning and scheduling in

[74] Source: Avi Weinbroum et al. (2003), Efficiency of the operating room suite [WEE03]

[75] Source: K. Janus et al. (2009), Sind amerikanische Arzte zufriedener? - Ergebnisse einer internationalen Studie unter Arzten an Universitätskliniken [Jan+09]

Profession	*Title*	*Responses*
Doctors	Attending Surgeon	16
	Anaesthesiologist	25
	Resident Anaesthetist	4
	Total	**45**
Nursing	Nurse Anaesthetist	34
	Surgical Nurse	26
	Surgical Technician	16
	Others	15
	Total	**91**
	Grand total	136

Table 4.7: An overview of the survey response in the UMHS

the USA and Germany, have notable similarities. Therefore, it could be speculated that the perception and the creation of value dimensions in the ORs are the same; to verify this statement, a factor analysis by Backhaus et al.[76] used in BELOUGA project was extended on BELOUGA-M-project with a combined dataset of a total of 501 responses.

4.4.2 Hypotheses

Differences exist regarding the importance of the individual value dimensions (or factors) with regard to the overall satisfaction within the OR-WPS process area.

(a) Derive individual hypotheses on the basis prior studies considering similar contexts such as cultural differences in hospital settings, for instance, on the topic of job satisfaction.

(b) Find and test plausible hypotheses and apply to the specific context of OR-WPS and confirm/reject these theories: Is this true in the field that physicians/surgeons and nursing place so much emphasis on the ability to create an OR schedule?

- For example, as regards the acceptance of IT, there have been theories in the literature on how people use hardware/software or how they react when they need to use a new IT system.

[76] Source: Klaus Backhaus et al. (2018), Multivariate Analysemethoden [Bac+18]

- Hypothesis on autonomy in decision making, which implies, for instance, in OR-WPS communication to the surgeon regarding their OR schedule of a typical day.
- Skill-based staffing/scheduling, for instance, are training medical regulations in Germany stricter than in the USA.
- Labour law and collective bargaining regulations, for instance, are the regulations in the USA less strict than in Germany.
- Information and communication of ORs schedule in Germany was found to be of more substantial influence, as planning and its communication is expected and is hence predominant in the German system.

(c) It can be potentially verified via *regression analysis* by using

- regression on overall satisfaction on UMHS/BELOUGA-M set of data; and
- regression of overall satisfaction on BELOUGA set of data

To prove or disprove the hypotheses, a comparison of the correlation coefficients (β values) standardised in the regression analyses for significant differences can be pursued via

(a) t-test[77] for differences between 2-β's (beta's); and

(b) Cumming method[78]—overlapping confidence intervals (CI)

The results of these analyses are presented in section (5.5) of chapter (5).

4.5 Qualitative Study in OR-WPS Process Area

In the BELOUGA-M-project[79], a *qualitative data analysis* (QDA), as reported by Mayring[80], was applied to the data collected on the OR-WPS at UMHS. The goal was to elucidate the underlying reasons and gain insights by correctly interpreting the well-documented observations/interviews of the focused group of persons. The different

[77] Source: Ronald Walpole et al. (2012), Probability & statistics for engineers & scientists [Wal+12]
[78] Source: Geoff Cumming et al. (2009), Confidence intervals [CF09]
[79] Note: Extension of BELOUGA-project to the case of a hospital in Missouri (USA).
[80] Source: Philipp Mayring (2010), Qualitative content analysis - Theoretical foundation, basic procedures and software solution [May14]

roles of the OR-WPS are described in more detail in section (4.4) in figure (4.20). The premise of a *qualitative study* is an inquiry stating with a (central) RQ and (associated) sub-questions[81], which are summarised as follows:

> *(Central) RQ5: What insights can be gained from the qualitative data collected during the OR-WPS process discovery? What are the critical differences between the results of this analysis and the survey outcomes?*

The following sub-questions followed the central RQ5:

> *(Sub) RQ: How can one systematically conduct the investigation and collect the qualitative data about the intraday running of the OR-WPS process?*

> *(Sub) RQ: How can one create mutually exclusive and collectively exhaustive (MECE) categories of activities conducted by schedulers and test their validity?*

> *(Sub) RQ: How much qualitative sample data, in terms of days of observation, is needed so that results could tell something about the population?*

> *(Sub) RQ: How well do the results of qualitative analysis agree with the survey conducted at both BELOUGA and BELOUGA-M/UMHS?*

To answer the aforementioned RQs, an exploration of the OR-WPS process area through transcription of either mentioned or quoted or observed phenomena during the *job-shadowing* is indispensable[82]. The research method is explained in the following subsection.

4.5.1 Method

In order to conduct the QDA, the starting point was the survey in BELOUGA used as a basis and then customised for the case of UMHS hospital, as discussed in section (4.4.1). These aspects are illustrated in tables (4.8) and (4.9).

[81] Note: RQ design based on qualitative, quantitative, and mixed approaches by Creswell [Cre14]
[82] Note: The transcription was performed while keeping the data integrity intact.

Nr.	*Survey – question*
	Responsiveness of the OR schedule
20	As an individual, how do you rate the level of consideration of your wishes by the scheduler?
15	… the level of balance between your family and work?
21	… the ability to exchange your work-duty with your colleague on your own?
22	… the level of fairness in scheduling?
25	… the transparency and comprehensibility of general-purpose scheduling rules?
26	… the ability of OR staff to respond flexibly to last-minute need for changes?
23	… the level of satisfaction with policies around compensatory time off for the overtime?
24	… the possibility for you to be deployed in varying job roles? An example: You have skills and training to perform surgery both on an elective as well as a trauma patient, etc.
14	… the level of adherence to the predefined shift?
	Information and communication of the OR schedule
9	… the communication of the last-minute changes in the OR schedule?
13	… on-time notification of OR scheduling?
10	… the level of interdepartmental agreement about OR schedule?
11	… the availability of contact persons regarding changes in the OR schedule?
17	… the quality of the scheduling process?
18	… the ability of administration to handle unexpected changes in the daily schedule?
1	… your level of input into scheduling around your skills and working hours?
	Code of conduct in team
6	… the kind of team training measures (like building fixed teams) in the schedule?
16	… the level of compliance with policy and procedures by OR staff?
8	… the level of transparency in the information flow from the administration?
	Mutual appreciation
3	… the level of personal appreciation you receive from nurses and other physicians in the OR?
1	… the level of cooperation among you (surgeon/physician, anaesthesiologist, nurse anaesthetist)?
2	… the level of cooperation between you and the staff responsible for OR scheduling?
4	… the level of personal appreciation received from the OR administration?

Table 4.8: The questionnaire used for the survey in the BELOUGA-M OR-WPS research project with final N_b categories in bold letters

$Nr.$	$Survey-question$
	Qualified personnel deployment
28	… allocation of staff with specialities?
27	… staff configuration during a surgery?
5	… the staffing mix in the OR?
29	… the availability of advanced training and continuing education?
	Legal working hours and collective agreements
30	… policies about legal working hours and wage standards?
31	… the actual implementation of legal working hours and wage standards?
	Timely announcement of the planned OR schedule
13a	… on-time notification of vacation planning?
13b	… on-time notification of shift planning?
32b	… your satisfaction with the scheduling systems (such as handwritten, computer-aided, etc.) for your shift?
	Enabling components for the OR planning and scheduling
32a	… your satisfaction with the scheduling systems for general OR?
33	… the provided in-house infrastructure (such as privacy room, break/cafeteria room, scrub room, etc.)?

Table 4.9: The questionnaire used for the survey in the BELOUGA-M OR-WPS research project with final N_b categories in bold letters

In the UMHS field study (job-shadowing), several individuals at different hierarchical levels involved in the OR-WPS process were interviewed and job-shadowed[83], as shown in an overview in table (4.10). These interviews are referred to as *observational protocols*.

Type	*Title*	*Participants*
Interviews	Attending Surgeon	4
	Anaesthesiologist	1
	Administration & Nursing	3
	Total	**8**
Observed	Surgical Nurse	3
	Nurse Anaesthetist	6
	Anaesthesiologist	6
	Total	**15**
	Grand total	23

Table 4.10: An overview of the survey response in the UMHS

The logical next step is to evaluate these interviews; this is referred to as *qualitative content analysis* (QCA). The interviews were transcribed. No audio recording of the interviews was performed; therefore, auditory data materials were not available. The transcription language was British English, so as to reproduce the original conversation. The transcribed interviews could be analysed using the MAXQDA software community edition, as reported by Kuckartz et al.[84]. During this study, the activities for three specific roles of the schedulers (nursing staff, anaesthesiologist and nurse anaesthetist) were identified and observed. These activities were also used for the work sampling analysis as described in section (4.3.1) and are listed in table (4.11). MAXQDA program enabled the digitisation of the category-based structuring and evaluation of the interviews via *coding*[85]. The closely related aspects or text components are allocated to codes or keywords with a likely heading during the coding process. These codes (categories) were created from within the data and based on prior knowledge of the OR-WPS process area. The function of a category is to organise and systematise the observed data. These categories are denoted as N

[83] Note: To ensure personal data protection, the names are anonymised.
[84] Source: Udo Kuckartz et al. (2019), Analyzing qualitative data with MAXQDA [KR19]
[85] Note: Also known as *code* or *keyword*.

number of categories, as shown in figure (4.22)[86]. MAXQDA supported the colour coding and memo if it needed a more extensive description to be more precise and clarify the uniqueness of the codes. In order to comply with the required openness, the formation of categories in qualitative research is usually inductive. A *deductive* procedure with predefined codes (categories) from the BELOUGA research project, as shown in tables (4.8) and (4.9), were used. They were known as N_b categories, where b can be any integer number, as shown in figure (4.22). It contrasts with an *inductive* procedure in which no categories could be present, and they are first derived and formulated from a new observation. If required, the codes were allocated sub-codes and sub-sub-codes. The transcription of the codes was confirmed by at least two independent researchers at UMHS, who could discuss and validate the coding of the interview text. The results of this analysis are presented in chapter (5), section (5.6).

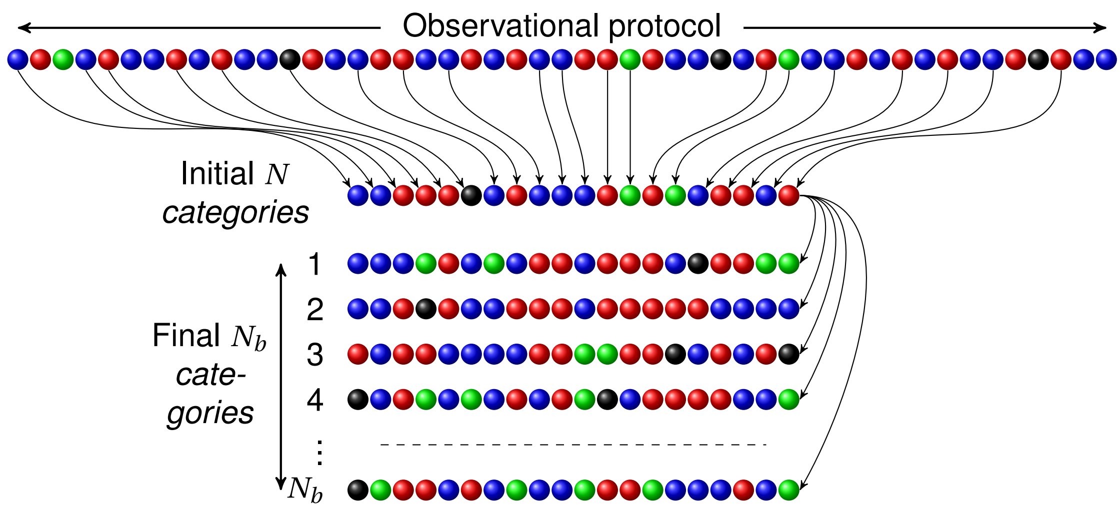


Figure 4.22: Explanation of procedure from observational protocol to categories in two steps

[86]Source: Bootstrap resampling by Germain Salvato-Vallverdu (https://texample.net/tikz/examples/bootstrap-resampling/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

CT.	Description	Nur.	Nur.Ana.	Anaesth.
1	Check-up on OR availability	✓	✓	✓
2	Check-up with Nursing OR Board Runner/Unit Clerk	✓	✓	✓
3	Check-up on Anaesthesiologists and Residents	✓	✓	✓
4	Check-up on Nurse Anaesthetist availability	✓	✓	✓
5	Add-on case staff scheduling	✓	✓	✓
6	Self checking patient at ward or staging area (ECT area)	✓	✓	✓
7	Self working in OR	✓	✓	✓
8	Rounding with other staff categories	✓	✓	✓
21	Check for patient availability/information	✓	✓	✓
22	Writing on board breaks and lunch	✓	✓	✓
23	Writing on board the staff schedule	✓	✓	✓
24	Discuss staffing with colleagues	✓	✓	✓
25	Discuss other issues with colleagues	✓	✓	✓
26	Check e-mail, myHR	✓	✓	✓
27	Case tracking on TV/Computer et cetera	✓	✓	✓
28	Sending/Receiving messages via pager, computer, phone	✓	✓	✓
29	Medical Information on SurgiNet and Teletracking	✓	✓	✓
30	Sending/receiving messages via pager, computer and phone	✓	✓	✓
41	Helping to supply the material	✓	✓	✓
42	Arrange equipment and material	✓	✓	✓
43	Transporting patient	✓	✓	✓
44	OR Board Runner and huddle meeting	✓	✓	✓
45	Prepare weekly staffing schedule	✓	✓	✓
51	Relaxing (coffee, wash-room, small-talk)	✓	✓	✓
52	Walking	✓	✓	✓
53	Lunch break for self	✓	✓	✓
54	Others (filled survey or discussion)	✓		✓
9	Self nursing help		✓	
10	Staffing issue due to residents		✓	✓
11	Opening an OR		✓	
12	Staffing issue due to lunch/breaks		✓	
31	Late start reporting		✓	
46	Prepare weekly staffing schedule		✓	
New	Cases moved from one OR to another or cancelled	✓		

Table 4.11: Categories (CT.) of the observational protocol during job-shadowing the nursing staff scheduler (Nur.), nurse anaesthetist scheduler (Nur. Ana.) and anaesthesiologist scheduler(Anaesth.). The *New* categories denote an identification of something found during data analysis of the observation.

4.6 Enterprise Architecture Focusing on OR-WPS

An objective of developing an EA, presented in chapter (6), is to showcase the realisation of the strategic goals of an enterprise (or, in this specific case, a healthcare service provider) via its (core or enabling) business processes and (core or enabling) IT applications. The underlying business processes of the core and enabling/supporting business functions, when working together seamlessly, can deliver a set of outputs for an enterprise. An integral of these outputs over a certain time frame would likely achieve the business goals. A potential benefit of using EA in advanced research is the realisation of the appropriate management of the conceptual requirements for implementing any multi-agent simulation (or similar concepts) and adequately managing the potential risk of not achieving the project and broader healthcare enterprise goals. On the basis of this premise, the EA investigation in this study began with a (central) RQ followed by a set of associated sub-questions[87].

> *(Central) advanced RQ: How can an EA framework support the introduction of computer simulation and help an enterprise manage its transformational IT landscape?*

The following sub-RQs followed the central research question (RQ):

> *(Sub) RQ: Which EA framework is the most suitable for this study and why?*

> *(Sub) RQ: Which EA deliverables support the stakeholders' views and how (where a deliverable is by definition something approved/accepted by its customer)?*

The following subsection summarises the efforts for addressing the central and sub-RQs. The setting and exploration for the RQs was in the OR-WPS enabling process area. The data were collected during the job-shadowing in a few German hospitals and one of the leading hospitals in Missouri, USA[88].

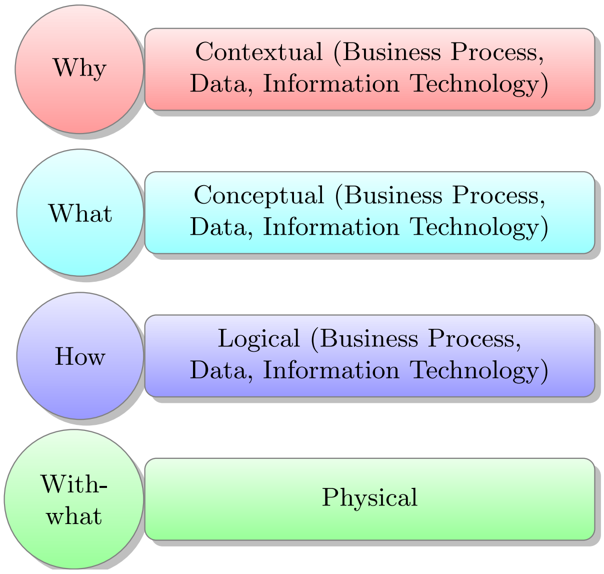


Figure 4.23: Abstraction level based on Integrated Architecture Framework (IAF)

4.6.1 Framework and Method

In section (2.2.4.3), the TOGAF® and its ADM are briefly introduced. In the same section, a table (2.2) presents the scope, along with a brief description of the phases. A detailed scope of this study and applicable phases of TOGAF® ADM are provided in table (4.12). The framework[89] is useful for sequentially considering the different architecture phases. This provides an *architecture content framework*[90]. Another option for content creation is the content model of the *integrated architecture framework* (IAF) proposed by van't Wout et al.[91] and the model of the *dynamic enterprise architecture* (DYA) proposed by Wagter et al.[92]. In this study, EA was applied to integrate the often fragmented focal areas into an integrative approach. The IAF with

[87]Source: John Creswell (2014), Research question design based on - Qualitative, quantitative, and mixed methods approaches [Cre14]

[88]Note: Data protection and scientific regulations were upheld during the data collection.

[89]Own definition: A framework is a flexible but comprehensive model that integrates multiple practices and tools while still offering most of the process.

[90]Source: Henk Jonkers et al. (2017), How to use the TOGAF® 9.1 architecture content framework with the ArchiMate® 3.0.1 modelling language [Jon+17]

[91]In-depth source: Jack van't Wout et al. (2010), The Integrated Architecture Framework explained [van+10b]

[92]In-depth source: Roel Wagter et al. (2005), Dynamic enterprise architecture (DYA) [Wag+05]

its well-known abstraction levels is illustrated in figure (4.23)[93]. The different abstraction levels in the IAF help decompose a large problem into manageable pieces. This is helpful in effectively addressing the RQs. Sections (6.3), (6.4), (6.5), and (6.6) of chapter (6) present the architectural models and descriptions regarding advanced research using the IAF.

[93]A descriptive diagram of TikZ tasks by Stefan Kottwitz (https://texample.net/tikz/examples/smart-description/) is licensed under CC BY http://creativecommons.org/licenses/by/4.0/

Phase	*Activity(-is)*	*In-scope*
Preliminary Phase	Prepare the organisations for fundamental changes through architecture projects. Create Architecture Capability, selection of tools and the definition of Architecture Principles	No
Requirements Management	The following steps are based on valid business requirements. Identified requirements flow in the subsequent ADM phases	Fully
Phase A: Architecture Vision	Setting the scope, constraints and expectations of this research project. Stakeholders identified validated business context and organisation's approvals.	Partially
Phase B: Business Architecture Phase C: Information Systems Architectures Phase D: Technology Architecture	Architecture for the following domains 1. Business 2. Information Systems - Application 3. Information Systems - Data 4. Technology - Current Technology Landscape For each, development of current landscape, gaps and future landscape are undertaken	Fully
Phase E: Opportunities and Solutions	Implementation of a PoC. Identification of ways of implementing the building blocks from earlier phases. Identify Transition Architecture.	Fully
Phase F: Migration Planning	Roadmap for implementation and Migration of legacy systems to achieve future Architecture	Partially
Phase G: Implementation Governance	Architecture Board, the Architecture Processes for an organisation, Contracts, Conformity	No
Phase H: Architecture Change Management	Continual monitoring improvement via change management process to satisfy the needs of an enterprise	No

Table 4.12: TOGAF® Architecture Development Method ADM based research project scoping due to time-frame of the research work and mandate

5 Result Analysis

Abstract: *This chapter presents the results of a semi-systematic literature review to devise a suitable modelling methodology to address the research problem considered in this study. The enabling business processes studied in both German and American hospitals are presented. Further, the results of the simulation experiments of the OR workforce daily scheduling, specifically for the German use case, are provided. The noteworthy results from a work-sampling study conducted in the American hospital—to obtain distribution functions for inputs to the simulation experiment—are also presented. The findings of a survey comparing the customers of the OR-WPS process area in an American and German hospital are summarised. Moreover, a qualitative data analysis of the interviews conducted at the American hospital are discussed.*

5.1 Semi-SLR for OR-WPS Simulation

Renewed Interest in Computer Simulation

From a system's perspective, providing healthcare services to the patient (external customer) is a complex interaction involving different actors (such as a nurse, a surgeon, a physician) providing approximately 4000 medical and surgical procedures by using more than 6000 different types of medications and several types of surgical procedures. Healthcare service provision processes are highly dynamic[1,2,3],

[1]Source: Diwakar Gupta et al. (2008), Appointment scheduling in health care: Challenges and opportunities [GD08]

[2]Source: Kemafor Anyawu et al. (1999), Healthcare enterprise process development and integration [Any+99]

[3]Source: R. Lenz et al. (2004), Towards a continuous evolution and adaptation of information systems in healthcare [LK04]

highly complex[4], increasingly multi-disciplinary[5,6], and ad-hoc[7]. Healthcare process is a generic term covering both medical treatment and organizational processes[8]. Currently, as do other industries, the health care service providers face open competition. The use of digital means to reach the organization's goals and modifying business models is prevalent in service sectors, including banking, financing, real estate, logistics, and healthcare. Healthcare delivery organizations such as hospitals pursue data-driven business models to ensure good patient health-related outcomes at the optimum costs and satisfy customers and employees. Computer simulation is one of the approaches to realising healthcare digitalisation.

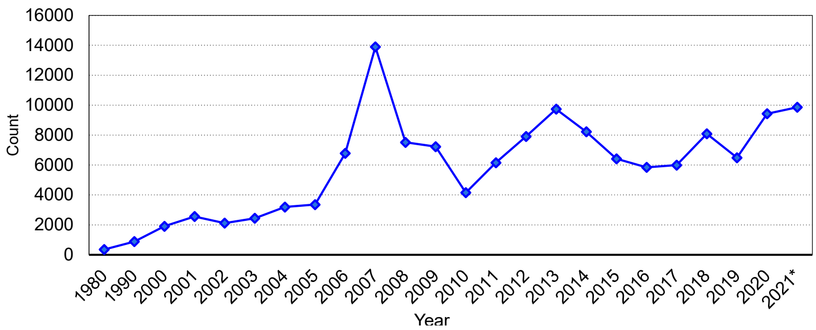


Figure 5.1: A plot of results of academic literature searched for combined keywords *hospital* and *computer simulation* with the provisional number for the year 2021

There has been renewed interest in academic research pertaining to the role of computer simulations in the healthcare domain, as evidenced by the multitude of studies. This is illustrated in the plot in figure (5.1)[9]. Studies started being reported in the 1980s, with a peak around 2007–2008 followed by a dip. Owing to the recent progress in computing power, massive data, communication technology, and interest shown by the businesses, there has been a trend of increasing number of reported studies until

[4] Source: M. Poulymenopoulou et al. (2003), Specifying workflow process requirements for an emergency medical service [PMV03]

[5] Source: Ibid - Diwakar Gupta et al. (2008)

[6] Source: Ibid - R. Lenz et al. (2004)

[7] Source: Ronny Mans et al. (2008), Process mining techniques: an application to stroke care [Man+08]

[8] Source: Álvaro Rebuge (2012), Business process analysis in healthcare environments - A methodology based on process mining [RF12]

[9] Source: Literature search using `https://app.dimensions.ai/` for the keywords "hospital" AND "computer simulation" performed in Nov, 2021

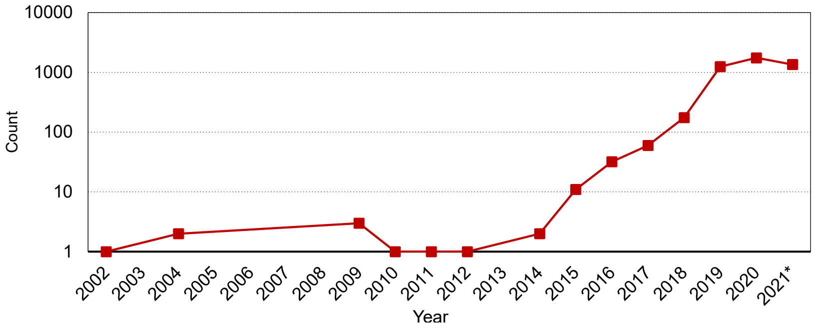


Figure 5.2: A plot of results of academic literature searched for combined keywords *hospital* AND *digital twin* with the provisional number for the year 2021

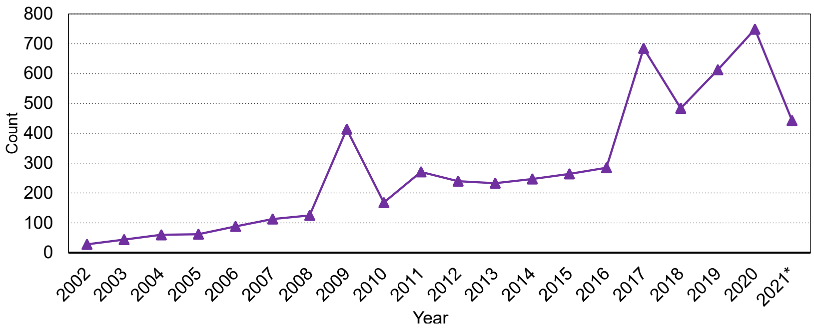


Figure 5.3: A plot of results of academic literature searched for combined keywords *hospital* AND *enterprise architecture* with the provisional number for the year 2021

2021. Kreutzer[10] explained the various phases of the Gartner hype cycle, such as the technology trigger, peak of inflated expectations, trough of disillusionment, slope of enlightenment, and plateau of productivity. The plot in figure (5.1) shows striking similarity with the Gartner hype cycle. The number of studies being published in this area indicates that the current phase is the plateau of productivity; this implies that simulation as a technology is finding widespread adoption and is considered a profitable proposition.

Eldabi et al.[11] provided a review of the legacy and future of simulation in the healthcare domain. Similarly, a literature search performed using keywords hospital with

[10] Source: Ralf Kreutzer (2015), Der Gartner Hype Cycle als prognostischer Hintergrund [Kre15]

[11] Source: T. Eldabi et al. (2006), Simulation modelling in healthcare: reviewing legacies and investigating futures [EPY06]

the digital twin[12] as shown in the plot in figure (5.2)[13] and enterprise architecture as shown in the plot in figure (5.3)[14] also yield similar trends. This suggests a growing interest to apply the concepts of DT and EA in the healthcare domain. Upon searching for articles by combining all these keywords, the number of published works since 2016 is as shown in figure (5.4)[15]. Nonetheless, the research emphasis must be placed on the human factor in healthcare provision.

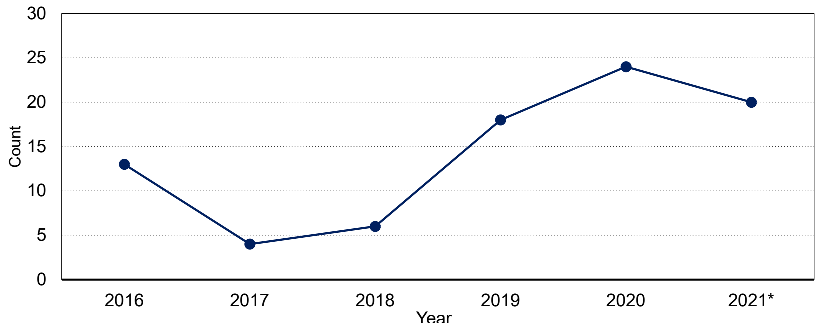


Figure 5.4: A plot of results of academic literature searched for combined keywords *hospital* AND *enterprise architecture* AND *digital twin* AND *computer simulation* with the provisional number for the year 2021

A Semi-SLR is capable of providing the right input and thus help gain a fundamental understanding of the current state of research. In the following sections, an introduction of the database and search terms followed by a list of literature collected and used to form a basis are presented.

Database and Search

Owing to their relevance to this study, several scholarly sources were selected to search for published research. They are listed in table (5.1). A search using logical *AND*, logical *OR* or combinations of the following keywords was employed to search the scholarly journal sources as shown in table (5.2):

[12]Note: The definition of a digital twin is provided in section (2.1.3).

[13]Source: Literature search using `https://app.dimensions.ai/` for the keywords “hospital" AND “digital twin" performed in Nov, 2021

[14]Source: Literature search using `https://app.dimensions.ai/` for the keywords “hospital" AND “enterprise architecture" performed in Nov, 2021

[15]Source: Literature search using `https://app.dimensions.ai/` for the keywords “hospital" AND “enterprise architecture" AND “digital twin" AND “computer simulation" performed in Nov, 2021

(a) Computer simulation

(b) Delivery of health care

(c) Quality improvement

(d) Business process

Approximately 235 articles were found to satisfy the keywords used for search criteria (described as the third step by Boren and Moxley). This was followed by the reading of the abstract and content of each found article—the fourth step in assessing the quality of articles. A list of the most relevant literature in the work context using search keywords is mentioned in the appendix in the tables (A.1), (A.2) and (A.3). Apart from the literature found and analysed in the Semi-SLR, many other published articles are also noteworthy. Dexter et al.[16] proposed a computer simulation approach to determine the appropriate amount of block time to allocate to the surgeons so as to maximise the ORs utilization. They have found a correlation of the input parameter *mean length* of time that patients wait before the surgery with ORs use. Another study by Hsieh et al.[17] focused on scheduling the patients by using a multi-agent simulation system. They used Petri net as the workflow language, implemented in JADE software platform, and distributed computing architecture for solving the problem. Paranjape et al.[18] reported on deep-dives in different issues related to MAS implementation in the healthcare domain, especially modelling. Using DES, Persson et al.[19] analysed management policies of ORs in Sweden, focusing on addressing the uncertainty in the demand of patient arrival and surgery duration so as to maximise the ORs utilisation. The outcome of the literature review followed by comprehension of the content of the literature content helped guide this study to determine whether a multi-agent approach is suitable. On the basis of the framework, it was identified that the OR-WPS business process and its agents, such as OR coordinator/scheduler/manager, are operating in an environment and have the following attributes:

[16] Source: Franklin Dexter et al. (2000), Scheduling surgical cases into overflow block time — Computer simulation [DMO00]

[17] Source: Fu-Shiung Hsieh et al. (2014), Scheduling patients in hospitals based on multi-agent systems [HL14]

[18] Source: Raman Paranjape et al. (2010), Multi-agent systems for healthcare simulation and modeling [PS10]

[19] Source:Marie Persson et al. (2010), Analysing management policies for operating room planning using simulation [PP10]

(a) The business process operates in a *dynamic* environment wherein the *numbers of (passive) agents*[20], such as the workforce for ORs, keep changing based on an OR plan.

(b) The involved agents, such as the different workforce categories, need to interact with the OR coordinator/scheduler to establish cooperation on the task through *communication*, *collaboration* and *interaction*. The workforce agents can be satisfied or dissatisfied depending on their experience during the OR scheduling process.

Database	Connected to
Ovid Medline	Medline, EMBASE, Cochrane Database of Systematic Reviews
EBSCO	Medline, CINHAL
Scopus	ScienceDirect, Elsevier, Scirus, EMBASE, Engineering Village, Compendex
Springerlink	Springer
Sage	Sage
Palgrave Mcmillan	Palgrave McMilllan
Europe PubMed Central	Europe PMC Consortium
PubMed	Medline
ProQuest	ABI/INFORM
IEEE Xplore	IEEE, IEEE Computer Society
Emerald Insight	Emerald Insight
Wiley Interscience	Wiley
ACM Digital Library	ACM
Web of Science	Thomson Reuters
Oxford	Oxford Journals
JSTOR	JSTOR
JASSS	JASSS
WSC (Winter Simulation Conference)	WSC Archieve

Table 5.1: The initial databases used in the SLR study and their corresponding sources

In order for a computer simulation to create value, it should be able to provide decision support to forecast—on the basis of the input parameters—the expected performance in terms of performance indicators of OR-WPS current-state (as-is) in an

[20]Note: Here, workforce members are *passive* as they are being scheduled, whereas OR scheduler/coordinator is an *active* agent, as they are proactively scheduling.

Database	Search keywords	Results
Ovid Medline	"computer simulation" AND "delivery of health care" AND "quality improvement"	41
EBSCO	"simulation" AND "healthcare" AND "business process" AND "improvement"	7
Scopus	"computer simulation" AND "health care" AND "business process"	11
SpringerLink	"simulation" AND "healthcare" AND "health" AND "care" AND "business" AND "process" AND "improvement"	3
Sage	"simulation" AND "healthcare" AND "health" AND "care" AND "business" AND "process" AND "improvement"	66
Palgrave Mcmillan	"simulation" AND "healthcare" AND "health" AND "care" AND "business" AND "process" AND "improvement"	26
Europe PubMed Central	"simulation" AND "healthcare" AND "process"	11
PubMed	"simulation" AND "healthcare" AND "business process" AND "improvement"	0
ProQuest	"computer simulation" AND "healthcare" OR "health care" AND "business process" AND "improvement"	14
IEEE Xplore	"healthcare" OR "health care" AND "simulation" AND "business process"	29
Emerald Insight	"simulation" AND "healthcare" AND "health" AND "care" AND "business" AND "process" AND "improvement"	18
Wiley Interscience	*Excluded from the study*	0
ACM Digital Library	"simulation" AND "healthcare" AND "process"	6
Web of Science	*Excluded from the study*	0
Oxford	"simulation" AND "healthcare" AND "business process"	0
JSTOR	"simulation" AND "healthcare" AND "business process"	3
JASSS	"simulation" AND "healthcare" AND "business process"	0
WSC (Winter Simulation Conference)	*Excluded from the study*	0
Total		235

Table 5.2: The database, search keywords and corresponding articles found used in the SLR study

experimental environment. Depending on the outcomes in a simulation, the coordinator/scheduler/manager should either change the OR plan or suggest improvements. A similar proposal was made by van der Aalst et al.[21] who also suggested that business process simulation had limited practical relevance owing to the time-consuming simulation model construction followed by rigorous validation procedure. In order to determine with which simulation methodology the agents, underlying business process, and data would be implemented, the use of a framework proposed by Bogg et al.[22], may be relevant. The deciding factors include (1) environment (open, dynamic or uncertain), (2) distributed (data, resource or task), (3) interaction (negotiation or deliberation), (4) efficiency, (5) reliability, (6) robustness, (7) flexibility, (8) responsiveness, (9) indeterminism, and (10) concurrency. On the basis of all these criteria, for OR-WPS, the multi-agent approach MAS was found to be the most suitable. A MAS can be developed from scratch by using common programming languages such as FORTRAN and C++[23], or contemporary programming languages such as Java and Python. Since the late nineties, many computer simulation development environments have been available for both research and practice. A recent survey of these platforms and the matrix of their attributes have been reported by Kravari et al.[24]. Haiyan et al.[25] set an example of developing a simulation environment based on *workflow* and *MAS* from scratch. However, the *off-the-shelf* simulation software can deliver value via reduced *time-to-market* and *standardization*, which were predetermined architecture guiding principles of this study. This is explained in detail in section (6.3.6). Both the findings from the literature review and the guiding architecture principles helped decide the simulation environment, as described later in this chapter.

Based on the aforedescribed survey results and experience with other research projects, a few application components were considered for the multi-agent simulation of OR-WPS as shown in figure (5.5). These include JACK Sim, JADE, AnyLogic,

[21] Source: W. M. P. van der Aalst et al. (2010), Business process simulation - How to get it right? [van+10a]
[22] Source: Paul Bogg et al. (2008), When to use a multi-agent system? [BBL08]
[23] Source: James Nutaro (2010), Building software for simulation [Nut10]
[24] Source: Kalliopi Kravari et al. (2015), A survey of agent platforms [KB15]
[25] Source: Zhao Haiyan et al. (2007), A business process simulation environment based on workflow and multi-agent [HJ]

NetLogo, and Repast Simphony. The specific implementation of any of this multi-agent software in simulating enabling processes such as OR-WPS or PTL were also considered. Their evaluation criteria included *business fit*, *cost fit*, and *strategic importance*. These criteria had ratings from *bad* to *not applicable* or *no entry* to *very high*. AnyLogic Personal Learning Edition (PLE)[26], the ultimate choice, is a multi-method simulation platform supporting the ABMS approach. The users can capture the complexity and heterogeneity of multiple scales in space and time at any level of detail because of the *low-code* development platform (LCDP), as mentioned in section (4.2.5), combined with JAVA programming language for sophisticated applications. It could satisfy the primary requirements of this study. Following the selection of software solution AnyLogic PLE to create ABMS, the focus was on the assessment as to whether AnyLogic can deliver value for the E2E simulation value chain. AnyLogic can be used to *realise* the simulation of various enabling processes—in this case, specifically OR-WPS (and in another context, PTL). The realised software solutions are referred to as ServiceSim OR-WPS (in another context, ServiceSim PTL). For advanced data processing, MATLAB could be used to support the value chain. Thus, the matrix shown in figure (5.6) affords a view on the overall dependency between the services (business requirements) needed (ordinate) provided by different application components (abscissa). For instance, AnyLogic can be used to *realise* a service, which would use it as an *integrated development environment* (IDE) to create the ABMSs. Subsequently, the applications and their service provisions shown as a matrix in figure (5.7), were selected . The figure illustrates the roles of *process manager*, *performer*, *requester of improvement* and *subject matter expert*. These stakeholders are aligned via early consultation (ordinate) to different enabling processes (abscissa) realised by relevant application components such as ServiceSim OR-WPS.

There has been a growing interest in the concept of DT. This was indicated in a Semi-SLR conducted at the beginning of 2012 and in 2019. Based on the review process suggested by Boren et al.[27], a chronological analysis of the published articles in journals and conference proceedings within the mentioned time frame was performed. They are shown in table (A.4). The source database was “Google Scholar"

[26]Source: Andrei Borschchev (2013), Big book of simulation modeling - multimethod modeling with Anylogic 6 [Bor13]
[27]Source: Ibid - Boren et al. (2015)

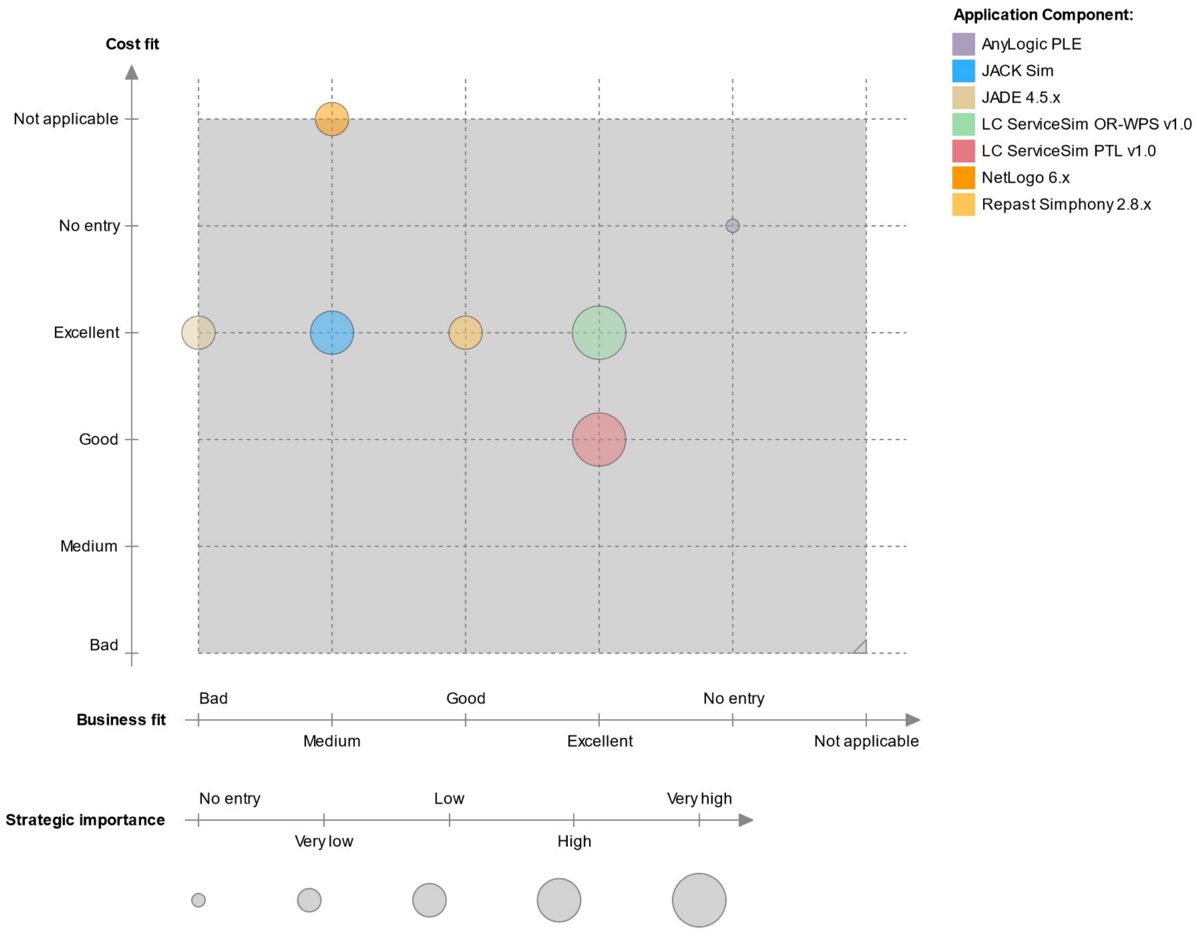


Figure 5.5: Portfolio view of the multi-agent simulation softwares considered (the so-called application components) consisting of comparison among them (Business-Fit versus Cost-Fit versus Strategic-Importance) in the research project

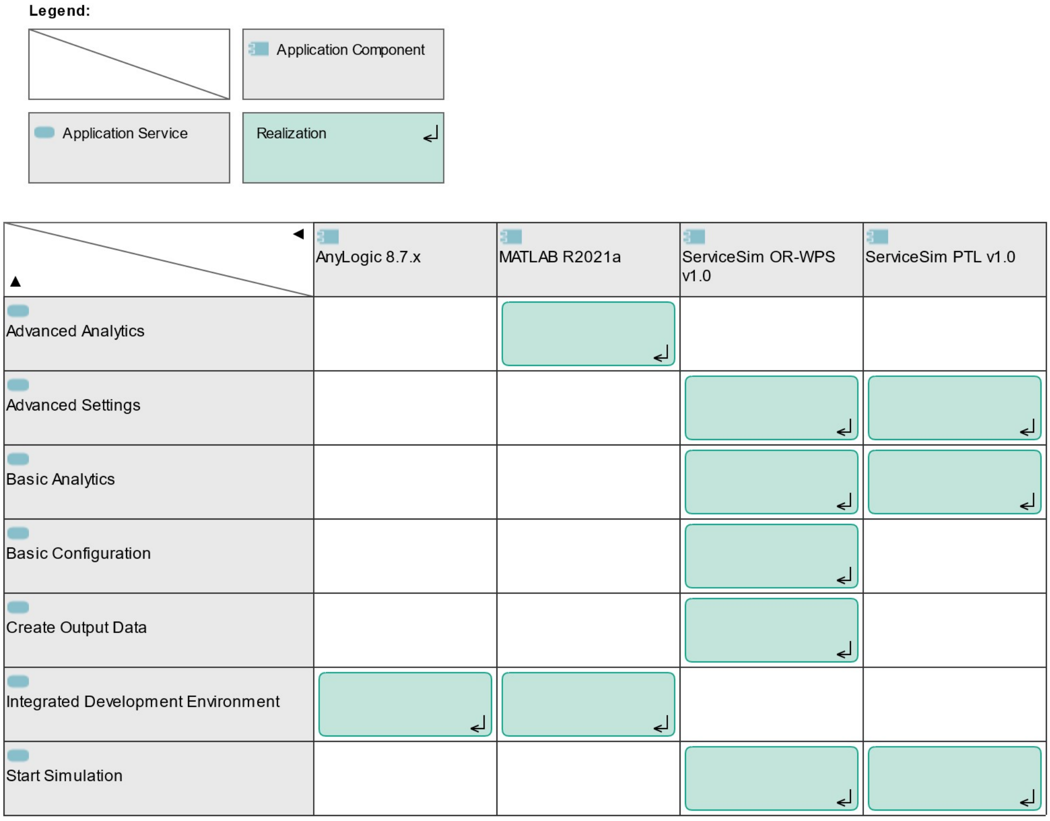


Figure 5.6: A Matrix view of application components realising corresponding application services modelled in ArchiMate®

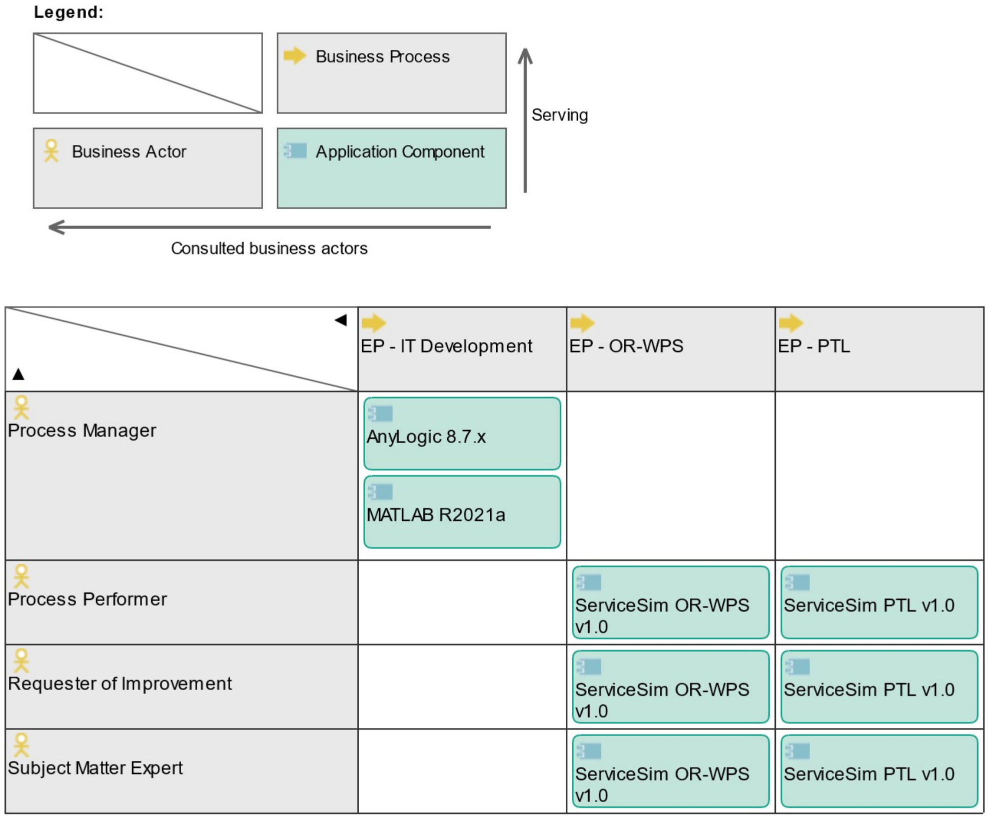


Figure 5.7: Matrix view of business processes *served* by application components and *consulted* business actors modelled in ArchiMate®

and the keyword was “Digital Twin". Intuitively, from the table, it could be concluded that DT originated as a term in aeronautical engineering and was subsequently used in manufacturing. A growing trend is witnessed with articles published mentioning DT, spanning diverse topics from serious-gaming domain to healthcare. The DT was first mentioned in 2015 at the Winter Simulation Conference. In 2018, a journal article by Karakara et al.[28] mentioned both DT and DES in the context of a hospital. At the time of writing this thesis, there was a lack of evidence of the use of ABMS or MAS for hospitals as well as of the proposal of DTs in this context.

Supplementary Analysis

The Semi-SLR, summarised in the previous section (5.1), indicated that suitable modelling of the transactional data for realising the simulation and the relationship of the model with the application components required an in-depth analysis. According to OpenGroup[29], an *application component* can be defined as in (5.22):

Definition 5.22. *Application component*

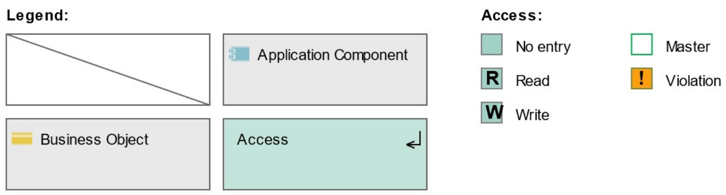
> *"An application component represents an encapsulation of application functionality aligned to implementation structure, which is modular and replaceable."*

In figure (5.8), already foreseen data objects (mentioned in previous chapters) are presented in a matrix form for easy analysis. Data objects are plotted on the y-axis, whereas on the x-axis, the application components that access the data objects are shown. In the intersection cells of the matrix, the type of access (write (W) or read-(R)) is indicated. Both ServiceSim OR-WPS and ServiceSim PTL, which are the specialised application of AnyLogic PLE, have lifecycles. Any update within AnyLogic PLE would directly influence the usability of specialised applications. Therefore, a *Gantt chart*, as shown in figure (5.9), can depict such a dependency and minimise any risk due to technical support issues in the future[30].

[28] Source: Abdallah Karakra et al. (2019), HospiT'Win: A predictive simulation-based digital twin for patients pathways in hospital [Kar+01]

[29] Source: https://pubs.opengroup.org/architecture/archimate3-doc/chap09.html

[30] Note: As this study sought to present a PoC, a risk to productive healthcare information systems at the premise of any hospital collaborating within the framework of this work was not foreseen.



	MATLAB R2021a	ServiceSim OR-WPS v1.0
Incidents		R
Manuel estimation of satisfaction		R
Number of anesthesia nurse		R
Number of anesthesiologist		R
Number of OR nurse		R
Number of ORs		R
Number of surgeon		R
Raw data - Cost	R	W
Raw data - Productivity	R	W
Raw data - Quality	R	W
Raw data - Satisfaction	R	W
Replacement staff		R
Staff planning		R
Time series of P, Q, C and S	W	
Vacation days per year		R

Figure 5.8: Matrix view of application components accessing the data objects modelled in ArchiMate®

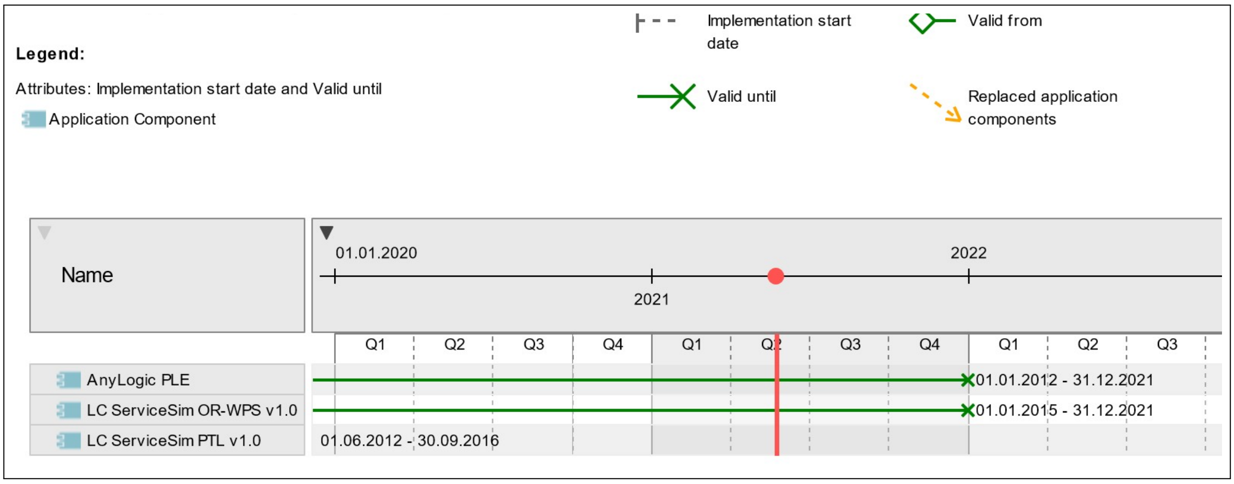


Figure 5.9: A Gantt view of the computer simulation applications to be implemented in this work with start date–end date. An estimated support date "valid until" of underlying AnyLogic PLE application is displayed as well modelled in ArchiMate®

5.1.1 Conclusion of the study

The following conclusions can be made based on tables (5.2), (A.1), (A.2), (A.3), and (A.4):

(a) Several scholars have published findings on computer simulations of business processes of healthcare service provision. Published works detail the use of multi-agent simulations to support decision support for different types of stakeholders in the healthcare domain.

(b) Some of the reported works mention the use of multi-agent simulation in different situations and particularly on the core processes, such as resource allocation in an emergency ward or the primary care. However, an in-depth analysis of the OR-WPS process area, focusing on customer satisfaction of the workforce engaged in the process, is lacking.

(c) Combining classical and value-based KPIs through multi-agent simulation has not thus far been reported. Heuristics to quantify the *customer satisfaction* in a simulation specifically for OR-WPS have not been investigated.

(d) This review leads to the conclusion that a *research gap* exists, concerning enabling business processes in decision support based on an agent-based/multi-agent simulation.

An in-depth analysis of the results of the literature review was pursued to select a platform for the implementation of an agent-based/multi-agent simulation; this can be summarised as follows:

(a) On the basis of the *research gaps* identified via the Semi-SLR, a computer simulation can be developed using open-source and proprietary multi-agent platforms, as shown in figure (5.5). Using a three-dimensional *business-fit*, *cost-fit*, and *strategic-importance* matrix, the most suitable choice was found to be AnyLogic Personal Learning Edition (PLE).

(b) A further in-depth investigation concluded that an application toolchain combining AnyLogic PLE for simulation and MATLAB for graphical representation of the data-sets from multi-agent simulation provide added value. Both specialised applications of AnyLogic, known as ServiceSim OR-WPS and ServiceSim PTL[31], together with MATLAB, can provide multiple services, as shown in figure (5.6).

(c) In the Semi-SLR, stakeholder management was identified as one of the essential components for gaining trust and future adoption of simulation tools in the hospital.

5.1.2 Advantage and limitation of the study

The insights gained from applying Semi-SLR in this study can be summarised as follows:

(a) Given the large number of published articles focusing on simulation in healthcare, the Semi-SLR afforded flexibility in choosing only relevant research articles.

(b) The study could broadly address the main RQ posed at the beginning of the study in a manageable time.

While applying the Semi-SLR in this study, the following limitations were noted:

(a) Semi-SLR is more subjective and is partially reproducible in terms of identified articles. In the future, a more focused review based on strict SLR can be performed to satisfy the reproducibility.

[31] Note: Outside the scope of this work, but mentioned elsewhere.

(b) The factors that define the selection of a simulation approach are qualitatively determined but could be part of published research in other domains. This aspect can be considered in future research.

5.2 Business Process of OR-WPS

The set of interviews performed revealed that the running of ORs is an integrated effort of a highly complex business process. The process discovery was executed at many hospitals, leading to a *reference process model*. The definition of a *reference process* is[32] provided in the definition (5.23), followed by figure (5.10), which depicts a reference process model in ArchiMate® 3.0[33] that is exhibited and is based on a model by Hastreiter et al.[34].

Definition 5.23. *Reference (Business) Process*

> *"Reference processes are used to determine and define the logistics service process to be compared. They form the basis for the benchmarking of different process executions by abstracting from individual characteristics as a structuring grid." [Wor+15b, p. 125]*

The OR-WPS is a complex hierarchical process involving several activities and time scales. In order to manage such complexity, the OR-WPS process area had to be segmented into yearly, half-yearly, weekly, and daily time scales with related activities of the process documented. The interviews, documentation, and validation with stakeholders (or subject matter experts) resulted in yearly, half-yearly, and weekly process diagrams in ArchiMate®, as shown in figures (5.11), (5.12), and (5.13), respectively. Although the OR-WPS business process is modelling is performed in the ArchiMate®, it is limited in its capability to model minute details. It can be confirmed from experience that when stakeholder engagement for high-level process alignment/description is the goal, ArchiMate® is the most suitable. However,

[32] Translated from texts in German to English
[33] Source: https://pubs.opengroup.org/architecture/archimate3-doc/
[34] Source: Stefan Hastreiter et al. (2015), Benchmarking-Studie OP-Personaleinsatzplanung [Has+15, pp. 221]

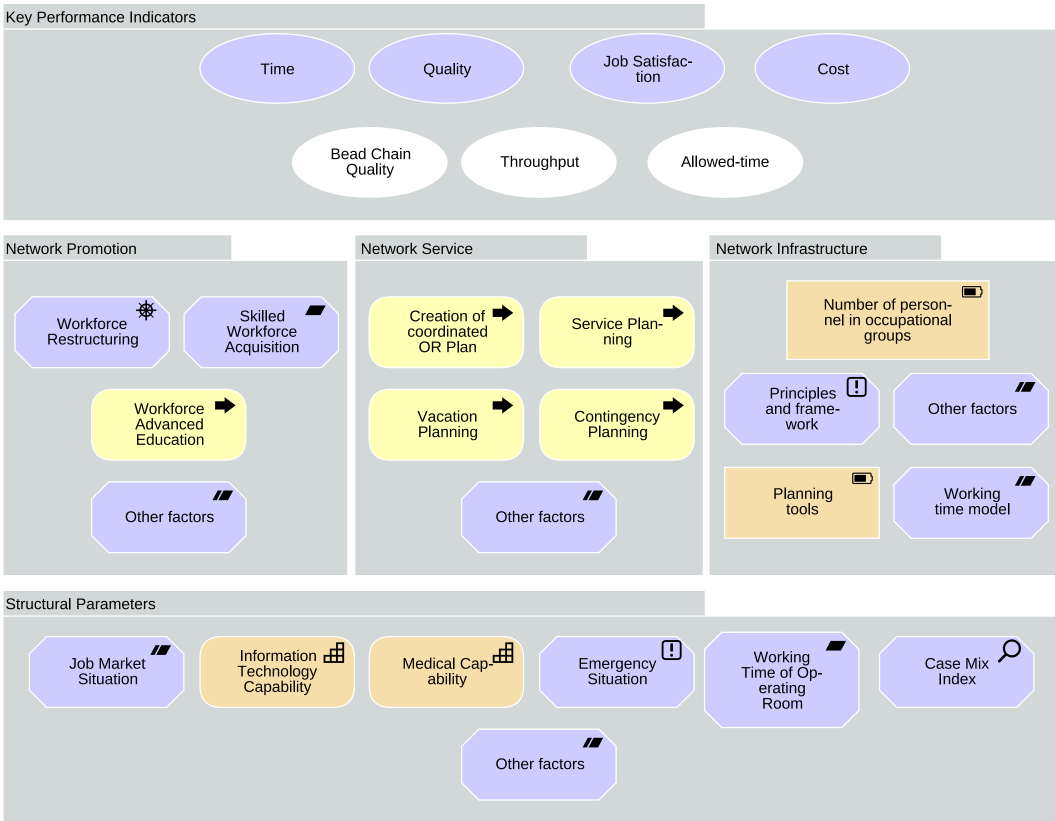


Figure 5.10: Reference process model of OR-WPS (based on one of the outcomes of BE-LOUGA project) in ArchiMate®

before any efforts toward digitalization in the form of a software solution, the roles, activity, and information flow details would be required. To this end, process-modelling languages such as BPMN 2.0[35] is the most suitable. Guidelines to transform from Archimate to BPMN are available, as described by Lankhorst et al.[36] and exhibited in table (5.3). On the basis of the translation to BPMN 2.0 and iterative interviews and validation, a detailed OR-WPS process area was documented as a specific instance of a typical German hospital as shown in its yearly (5.14), half-yearly (5.15), weekly (5.16) and daily (5.17) illustrations. The same interview procedure was followed in the American hospital, and a detailed OR-WPS process area was documented in its yearly (5.18), quarterly (5.19), monthly (5.20), weekly (5.21), and daily (5.22) manifestations.

ArchiMate	*BPMN*
Business Actor or Role	Pool or Lane
Business Process	Process
Triggering	Sequence Flow
Junction	Inclusive and parallel gateways
OR-junction	Exclusive and event-based gateway

Table 5.3: Mapping between ArchiMate® and BPMN 2.0

[35]Note: There is another way to model the processes known as *event-driven process chain* (EPC) by Sheer [Sch00], but BPMN 2.0 was selected in this study.

[36]Source: Marc Lankhorst et al. (2017), Combining ArchiMate with other standards and approaches [LAN17, p. 134]

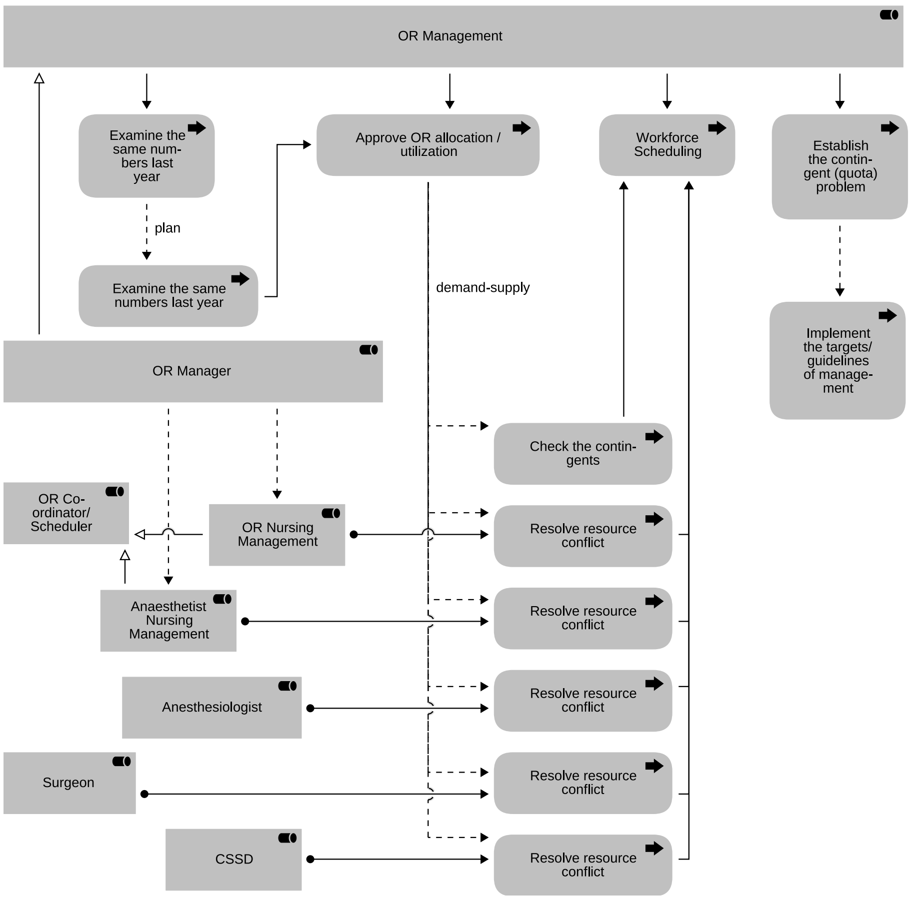


Figure 5.11: OR-WPS yearly workforce planning process for a German hospital operating room modelled in ArchiMate®

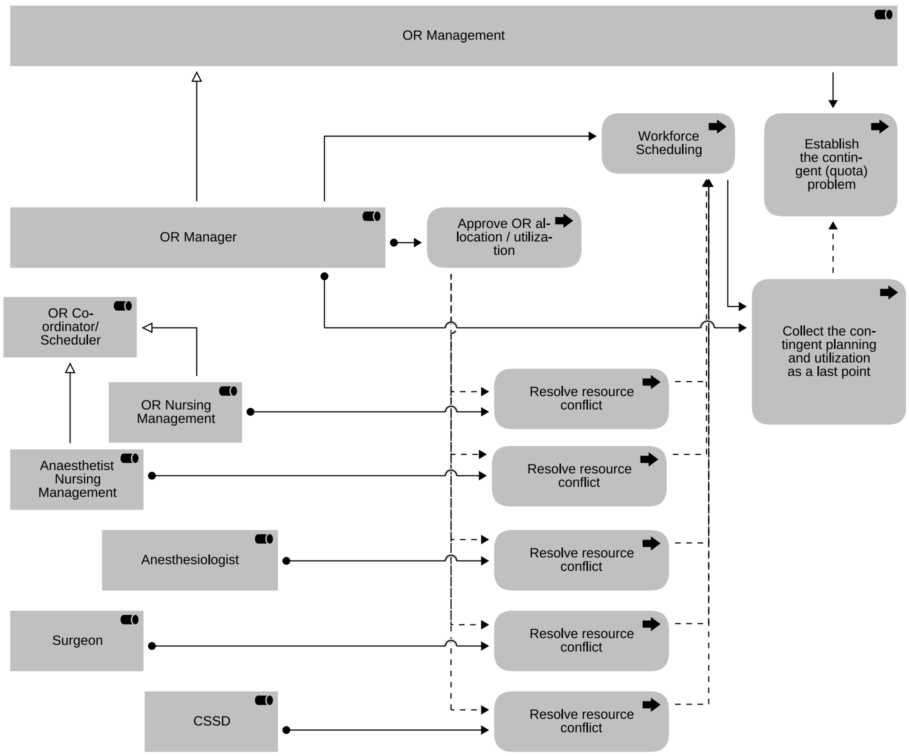


Figure 5.12: OR-WPS half-yearly workforce planning process for a German hospital operating room modelled in ArchiMate®

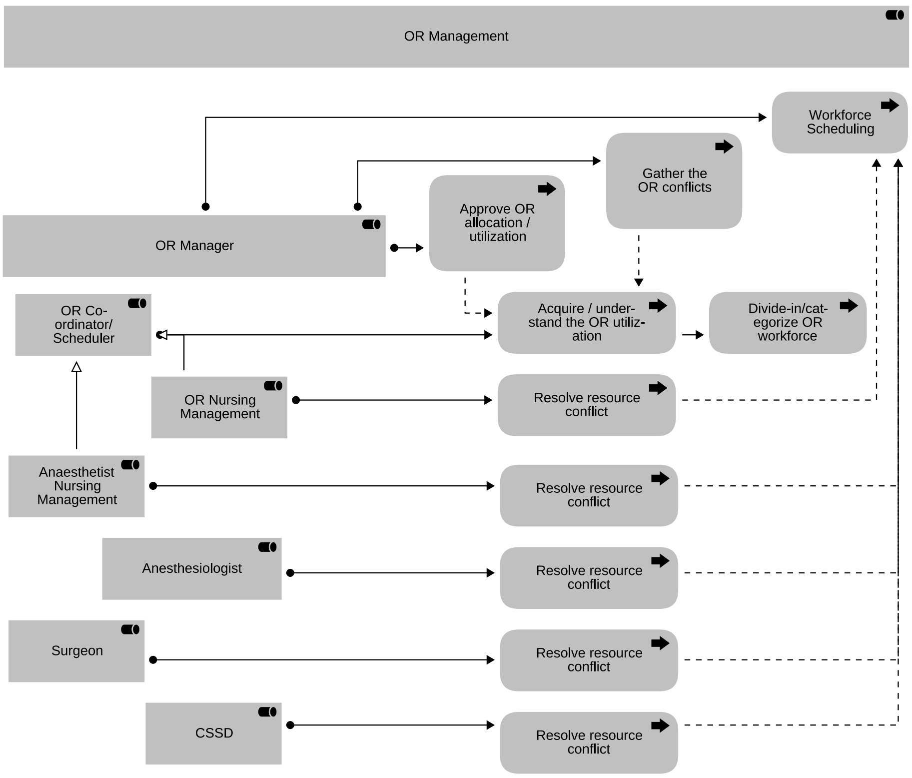


Figure 5.13: OR-WPS weekly workforce planning process for a German hospital operating room modelled in ArchiMate®

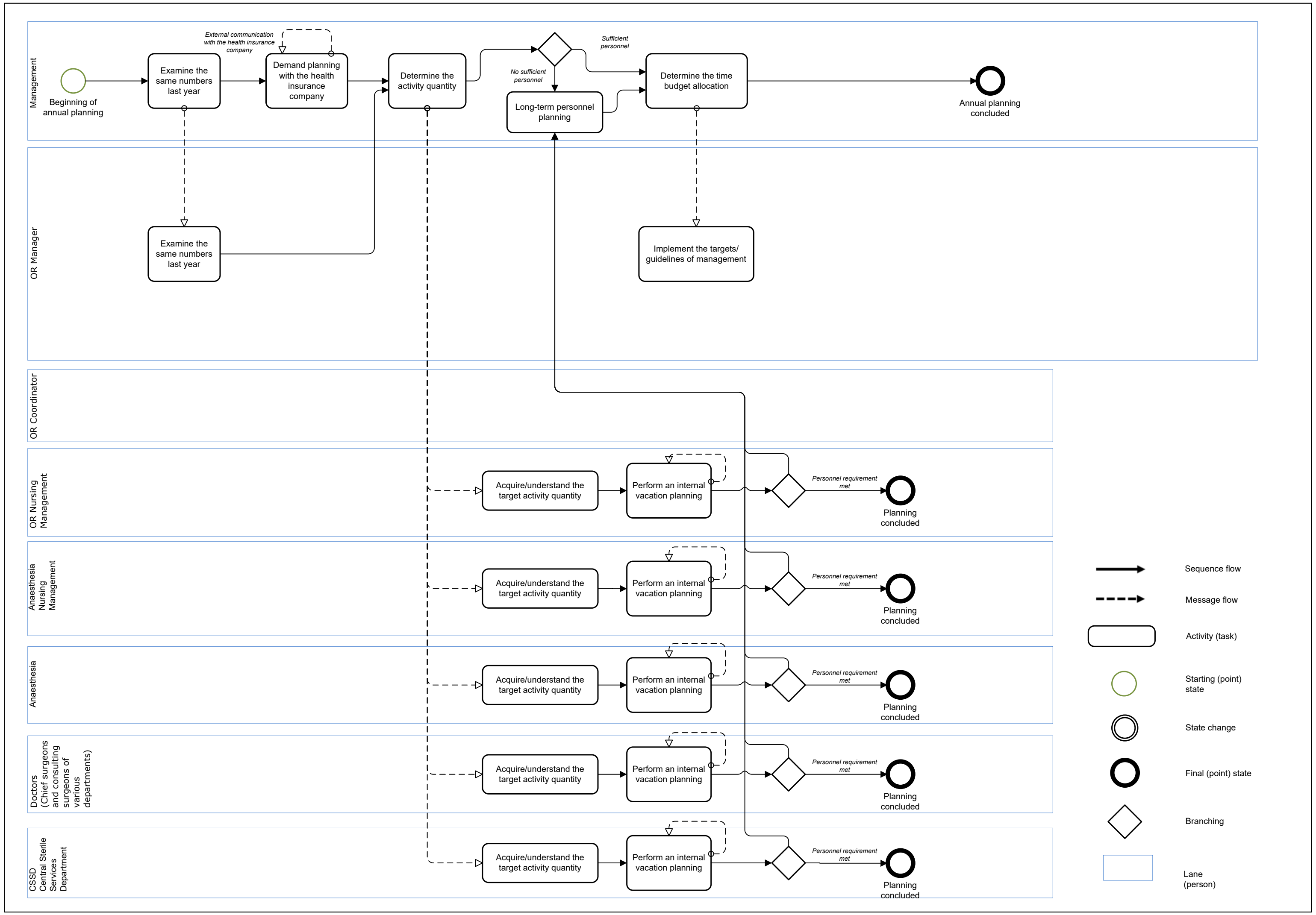


Figure 5.14: OR-WPS yearly workforce planning process for a German hospital operating room modelled in BPMN 2.0 language

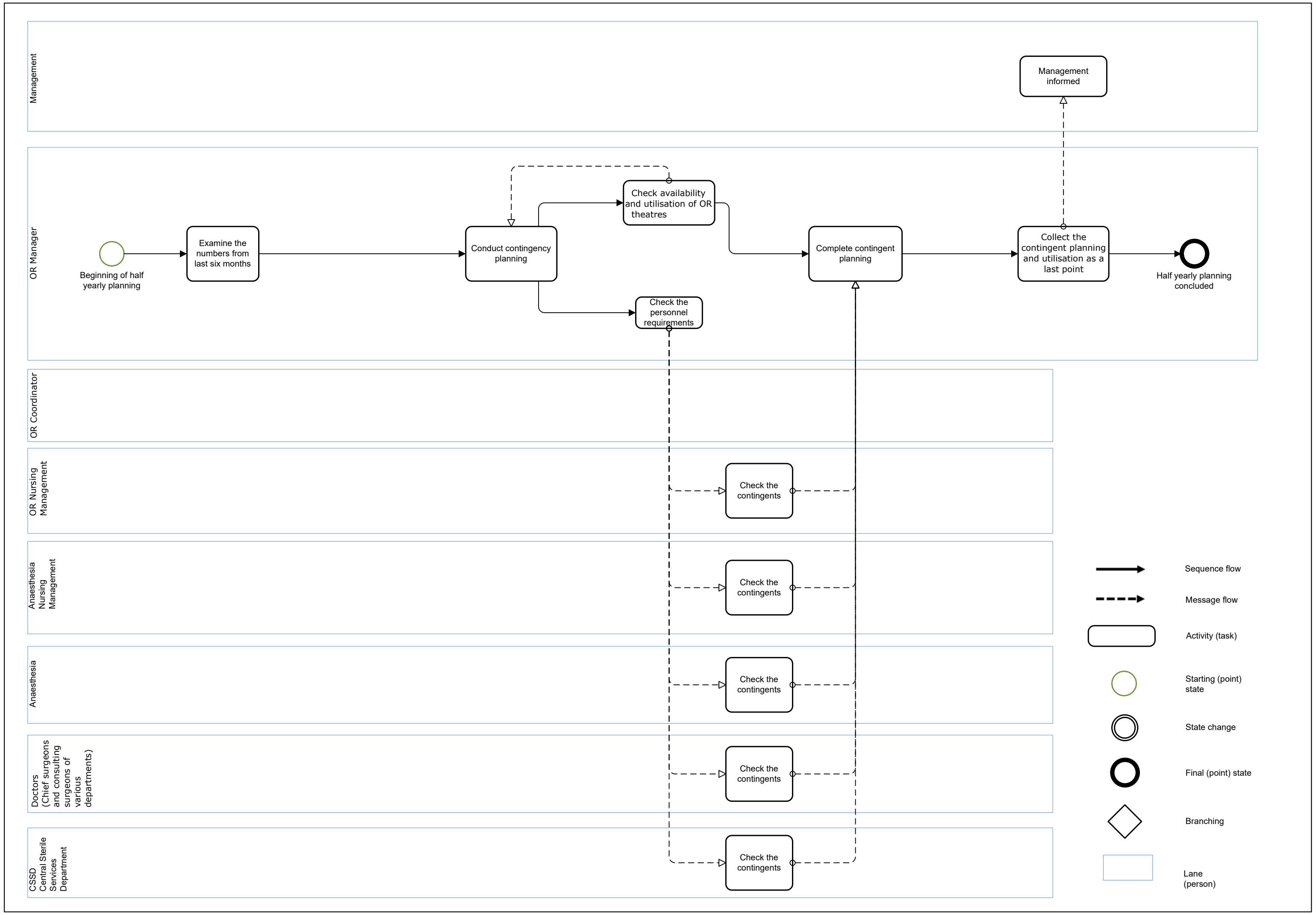


Figure 5.15: OR-WPS half-yearly workforce planning process for a German hospital operating room modelled in BPMN 2.0 language

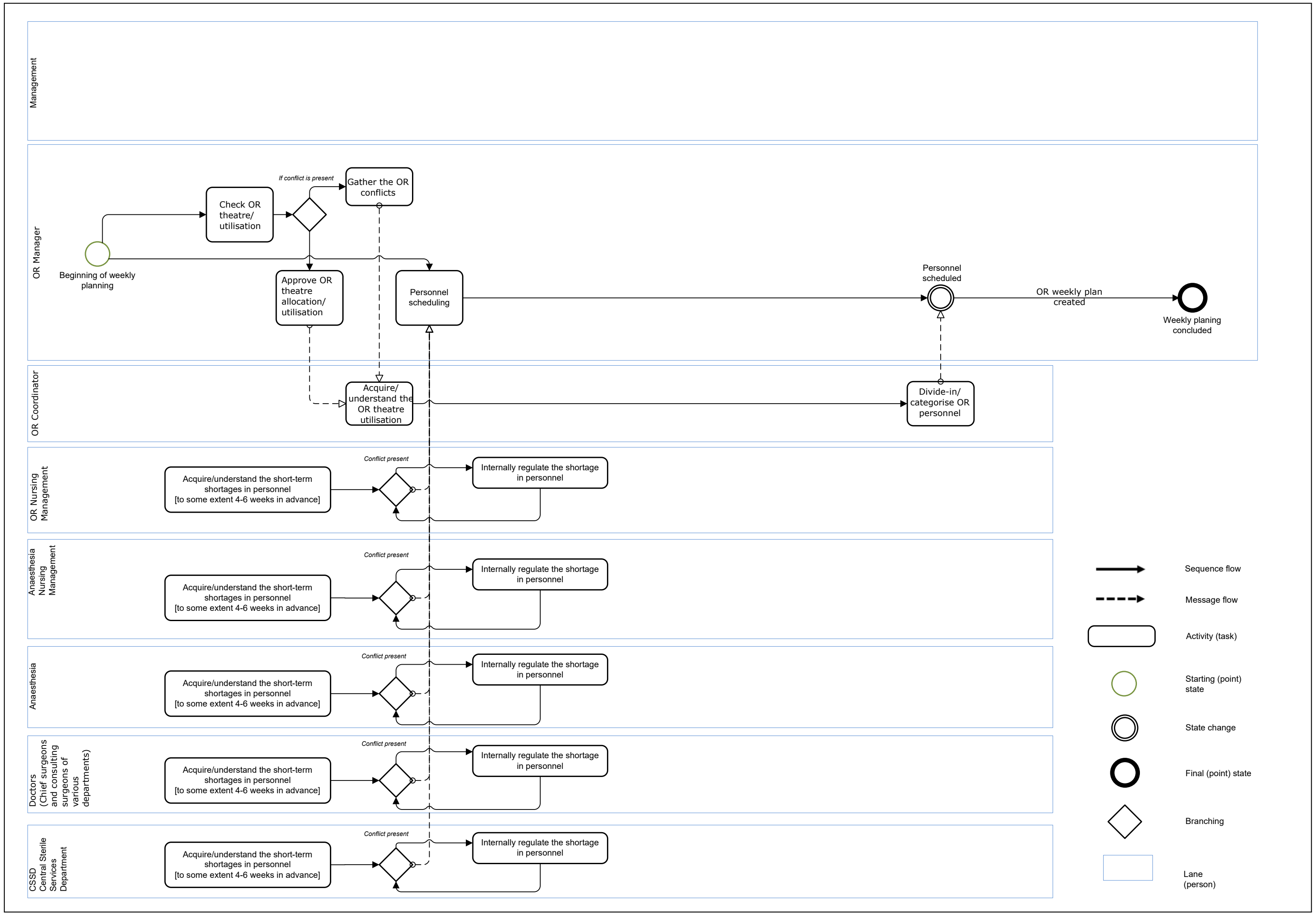


Figure 5.16: OR-WPS weekly workforce planning process for a German hospital operating room modelled in BPMN 2.0 language

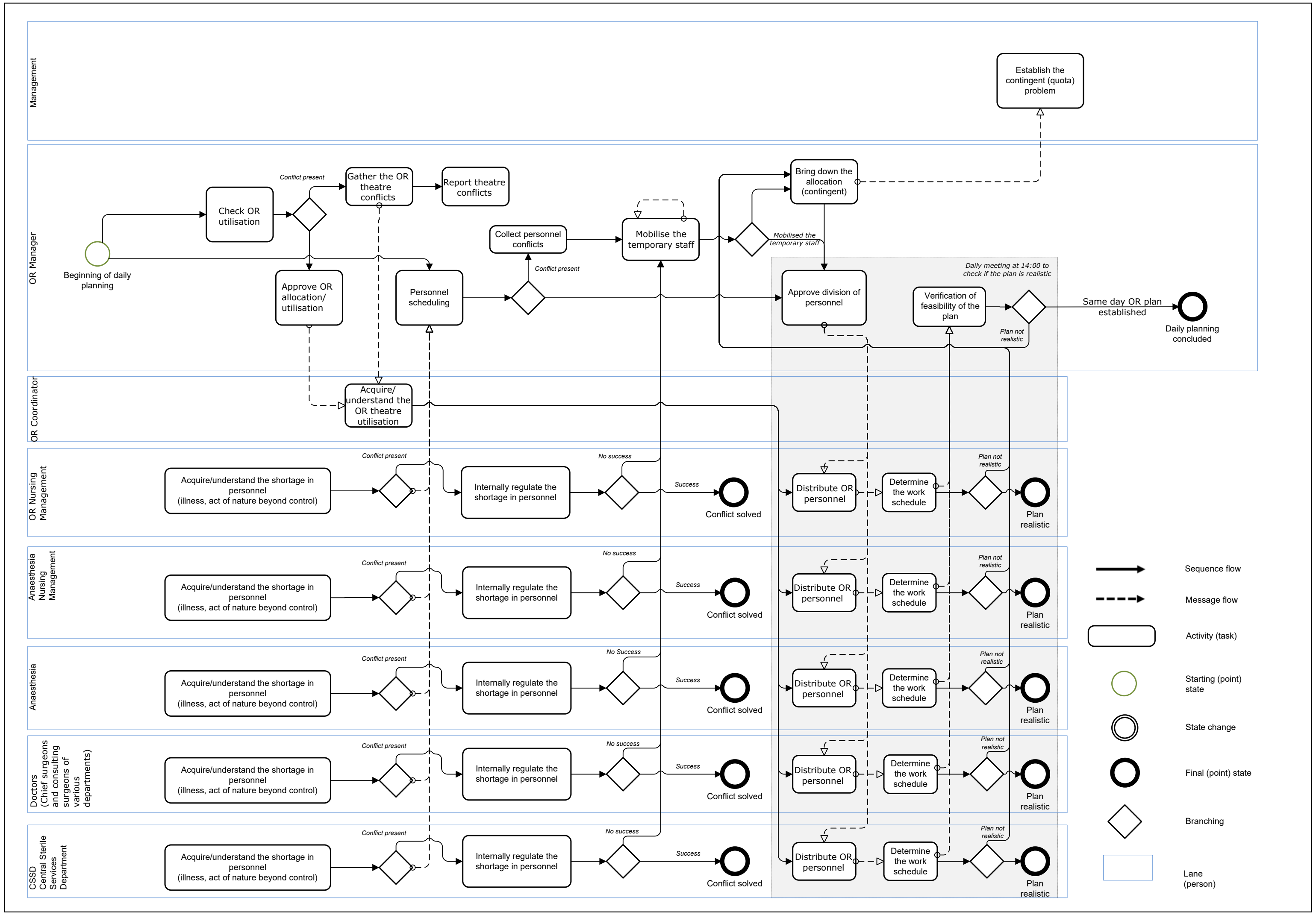


Figure 5.17: OR-WPS daily workforce planning process for a German hospital operating room modelled in BPMN 2.0 language

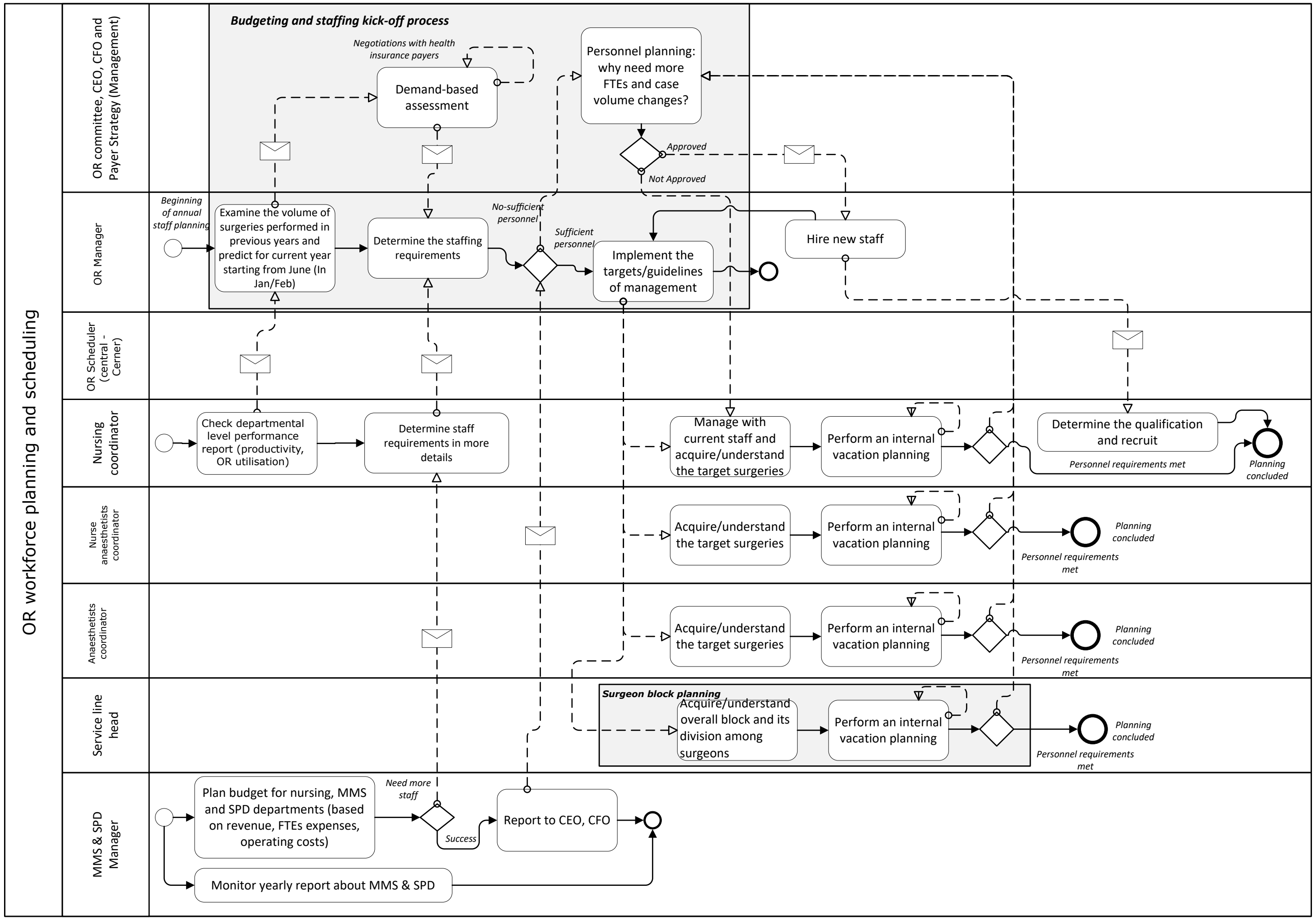


Figure 5.18: OR-WPS yearly workforce planning process for an American hospital operating room modelled in BPMN 2.0 language

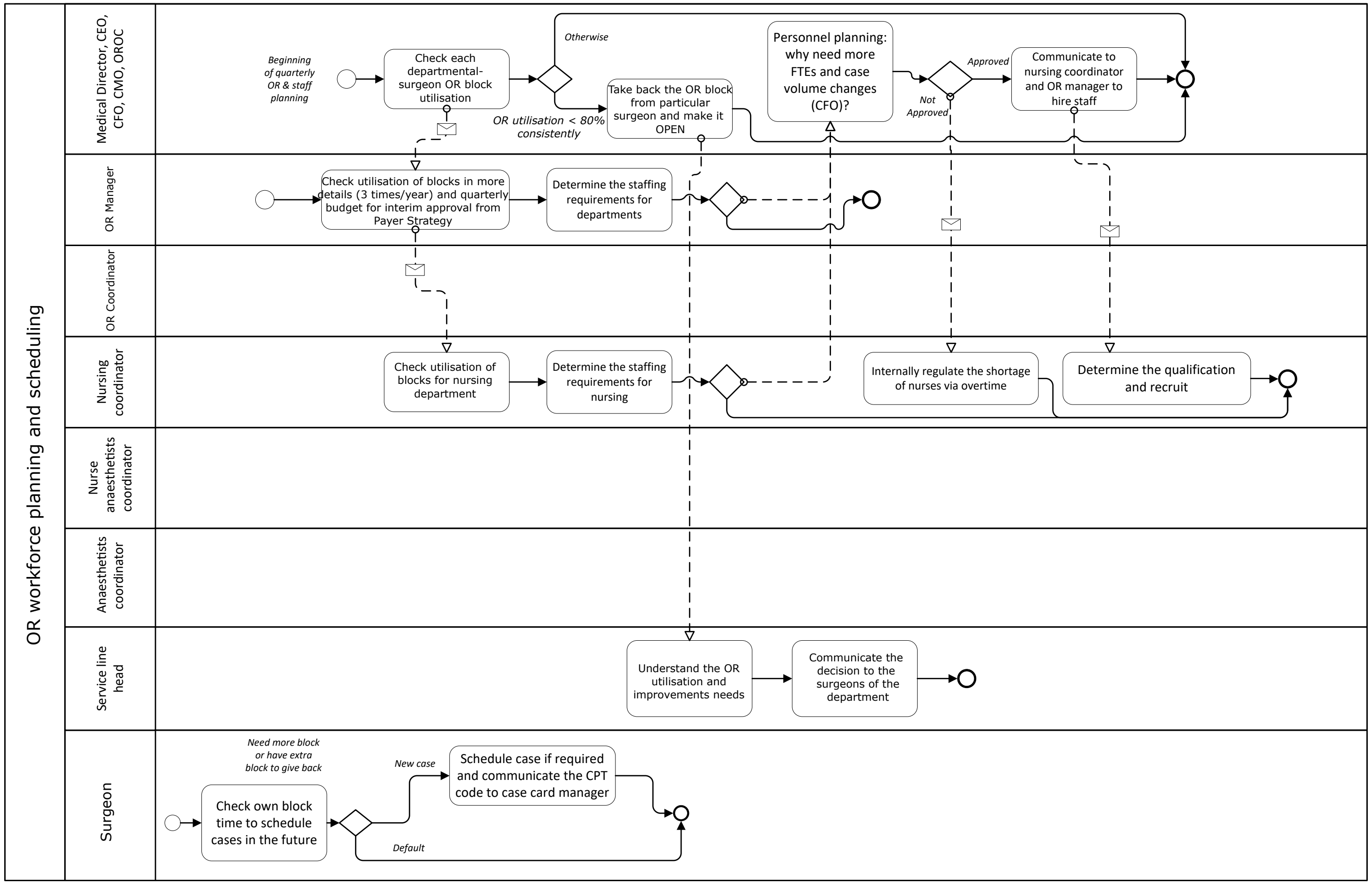


Figure 5.19: OR-WPS quarterly workforce planning process for an American hospital operating room modelled in BPMN 2.0 language

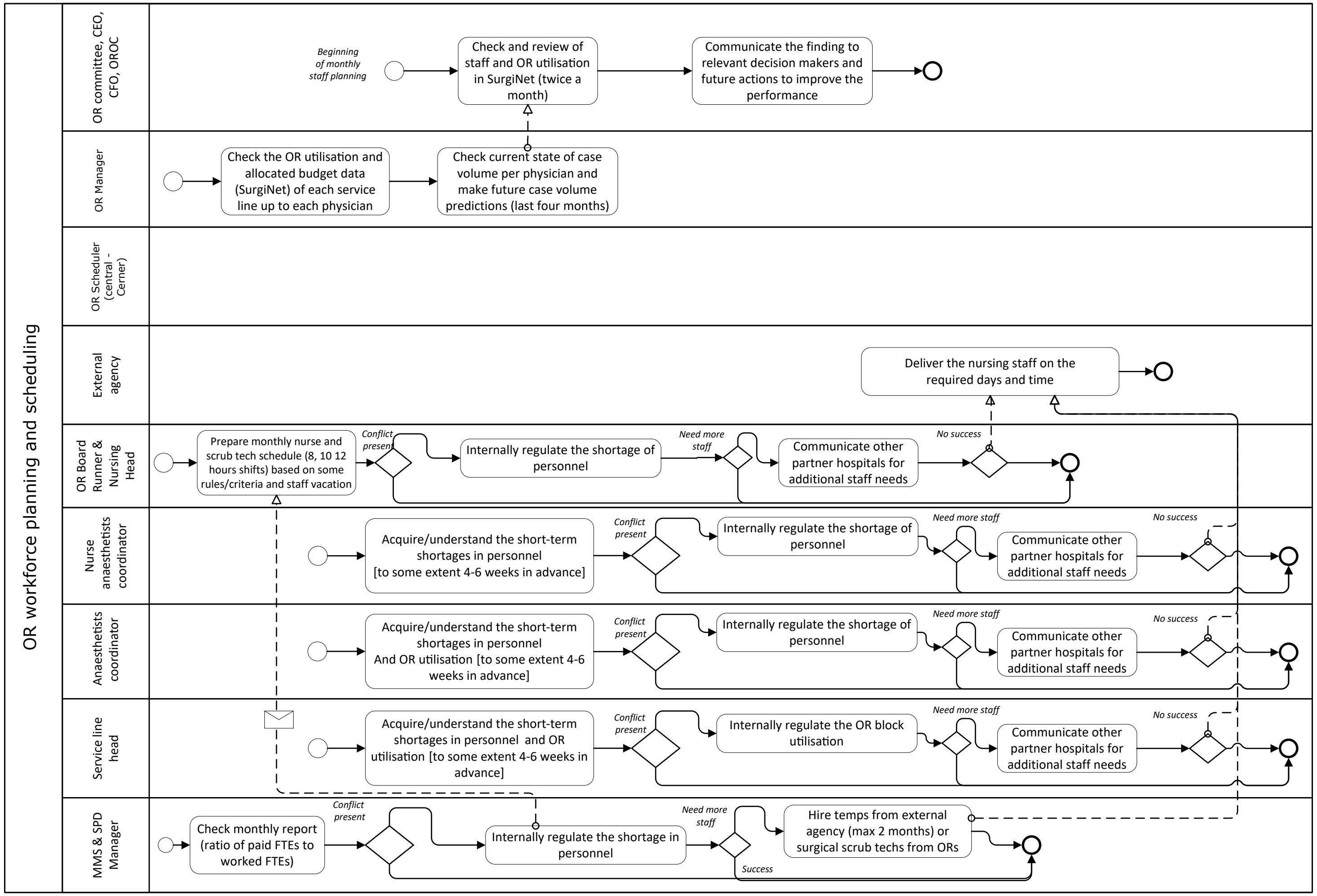


Figure 5.20: OR-WPS monthly workforce planning process for an American hospital operating room modelled in BPMN 2.0 language

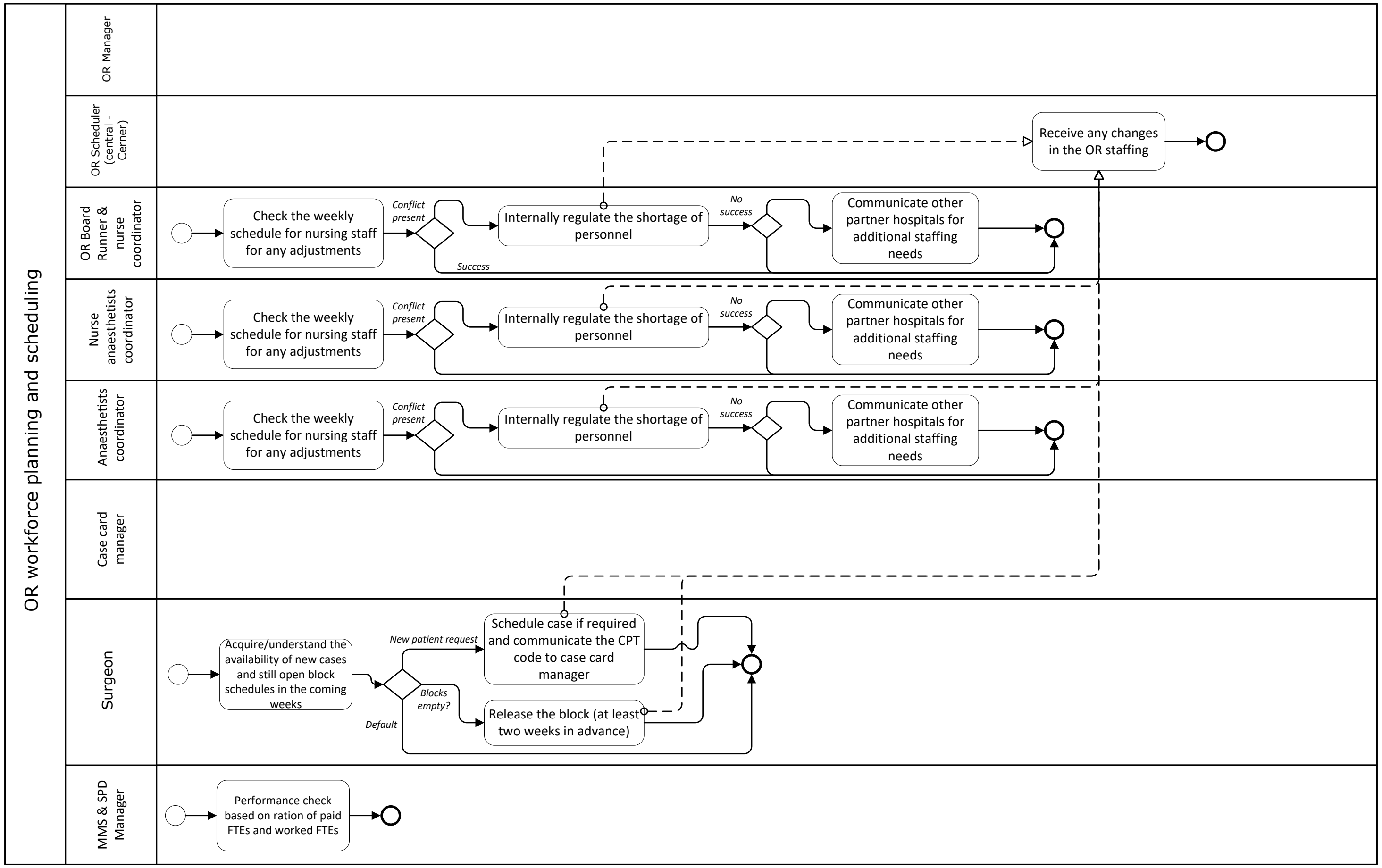


Figure 5.21: OR-WPS weekly workforce planning process for an American hospital operating room modelled in BPMN 2.0 language

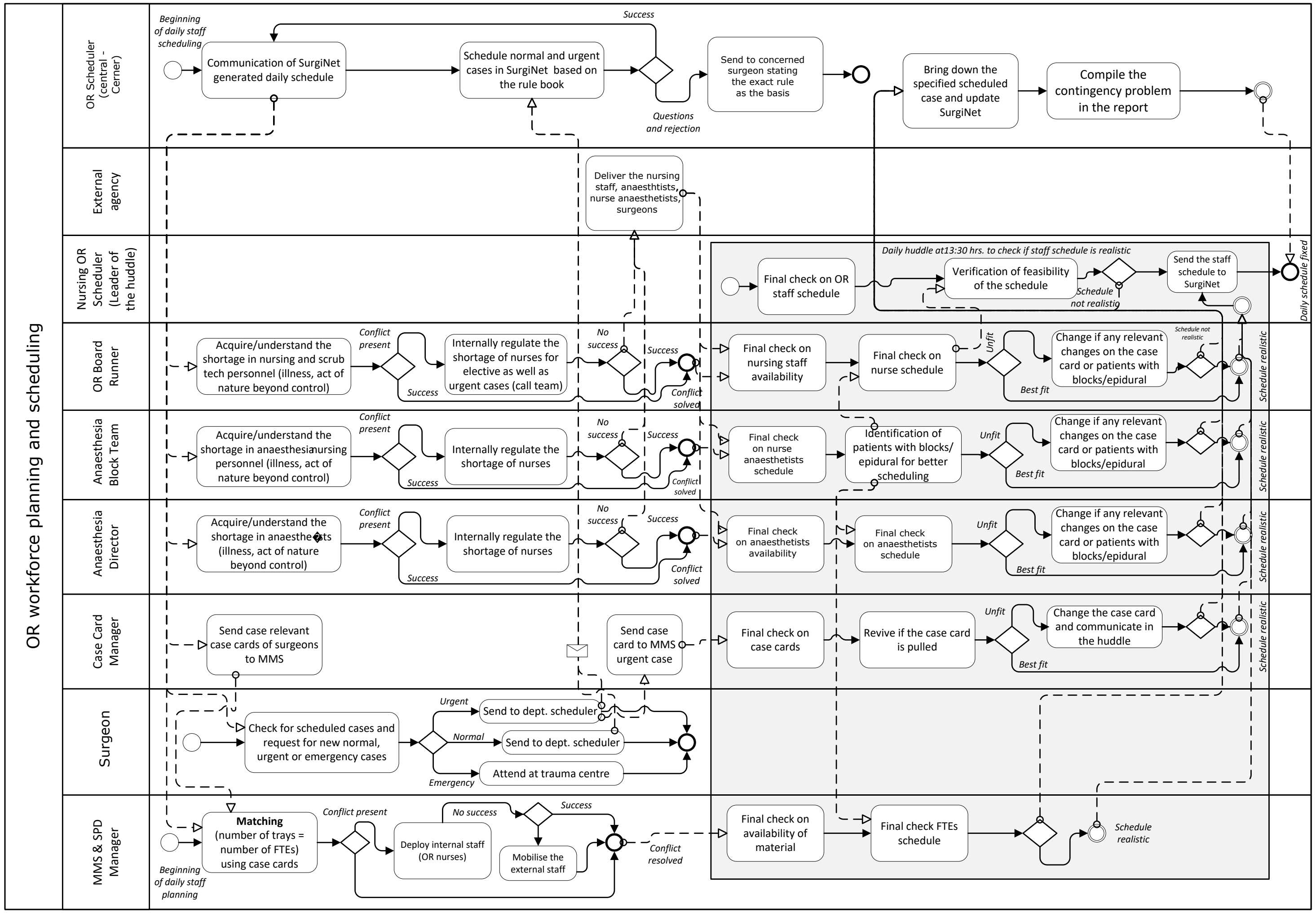


Figure 5.22: OR-WPS daily workforce planning process for an American hospital operating room modelled in BPMN 2.0 language

5.2.1 Conclusion of the study

The following conclusions can be drawn on the basis of figures (5.14), (5.15), (5.16), (5.17), (5.18), (5.19), (5.20), (5.21) and (5.22):

(a) From the perspective of content, OR-WPS is a complex enabling business process that uses cost-intensive hospital resources to provide one of the most important outcomes for both patients and the hospital. The timespan and stakeholder involved can be observed and documented in multi-scale terms.

(b) Except for a few differences in the process activities between the two hospitals (i.e. the one in Germany and another in the USA), they are mostly similar. Most of the differences exist in the weekly and daily activities of the OR schedulers.

(c) From the perspective of the research objective, the BPMN language is found to be the most appropriate for creating models suitable for computer simulations, thus confirming extant knowledge.

5.2.2 Advantage and limitation of the study

The insights gained from applying process discovery and modelling in this study can be described as follows:

(a) The discovery phase provided sufficient background knowledge of the OR-WPS process area and can be later utilised to create a valid simulation model.

(b) A process model at such a detailed level can have multiple utilization. It can be part of the process landscape of the hospital at a high level or the creation of process-mining background information or the starting point for discussions on digitalisation.

During the process discovery and modelling performed as part of this study, the following limitations were observed as well:

(a) Process discovery phase is resource intensive and therefore needs clear goals such as scope, accuracy, and available time.

(b) The process was documented on the basis of interviews and was validated; however, this does not necessarily confirm that the real-world operations are conducted in the same manner.

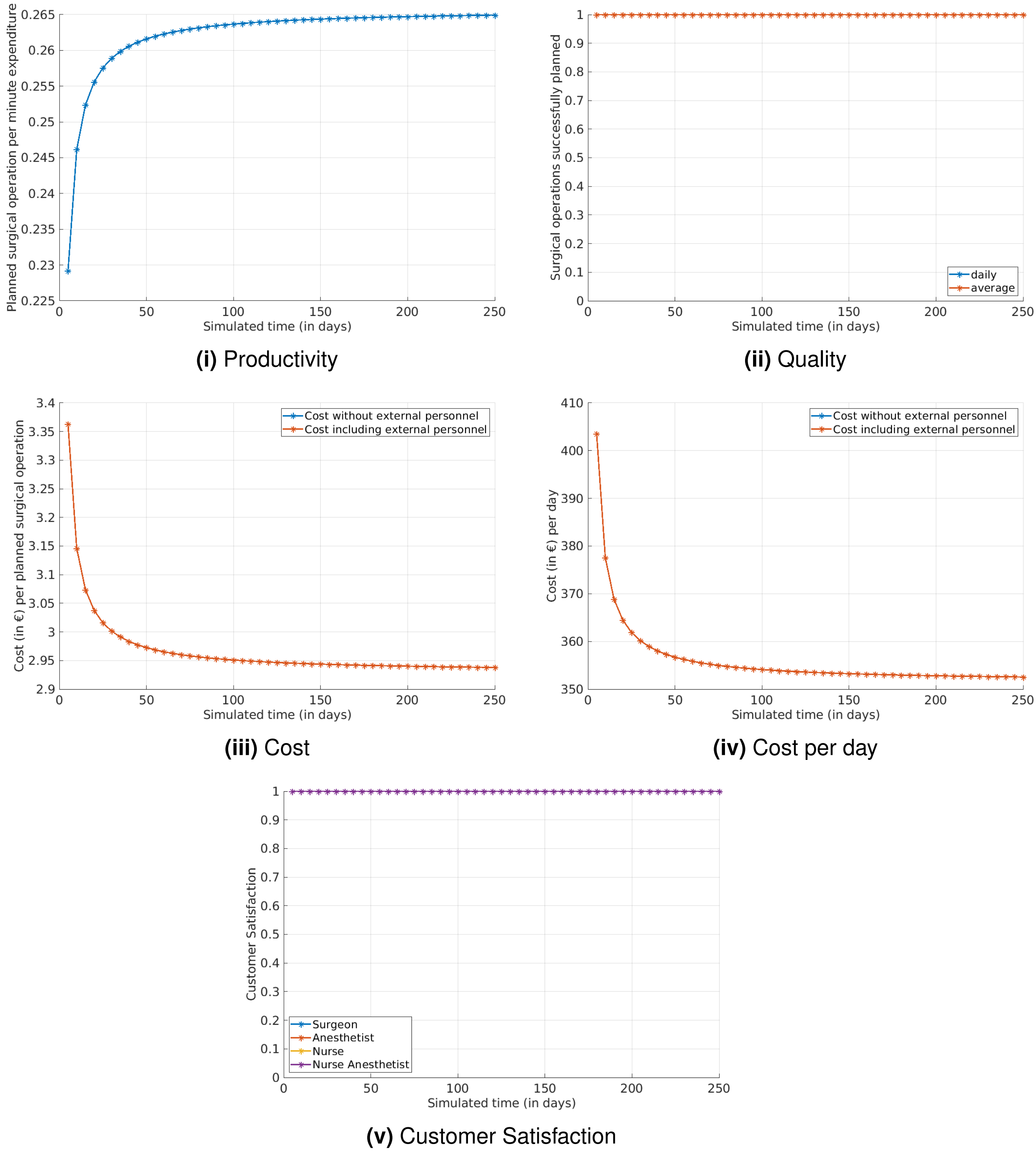
5.3 Multi-Agent Simulation of OR-WPS

In section (2.1.4) describing the simulation experiments, specifically in figure (2.7), achieving more findings with lesser effort through the appropriate design of experiments is indicated. In the design of a case study as mentioned in section (4.2.7), the experimentation strategy would be to use the ServiceSim OR-WPS multi-agent simulation tool to maximise the knowledge gained through experiments. In the following sections (5.3.1), (5.3.2) and (5.3.3), the case study[37] results and their analyses are presented.

5.3.1 Case 1: Yearly planning for the OR

The hospitals prefer to determine the workforce hiring strategy for the next year based on the historical utilization of the ORs. Therefore, the OR coordinator/scheduler could perform experiments using the ServiceSim OR-WPS tool with a normal and more than a usual number of patients getting surgeries in the orthopaedic ORs . The results shown in figures (5.23), (5.24), (5.25), and (5.26) are discussed in this section. As shown in figure (5.23), in a scenario with 12 ORs for the entire working year with settings described in the figure description, productivity rises to a maximum of 0.265. In this case, the quality stays at one. However, the cost drops to approximately €2.95 and the cost per day drops to approximately €350, while customer satisfaction is at 100% for all[38]. If we experiment with ORs to 15, 18 and 21 in a year, the cost per day increases to around €420, €480, and €540, respectively. These results are as shown in figures (5.24), (5.25) and (5.26), respectively. The trends in productivity, quality, and satisfaction remain the same. The physical explanation is that when there are no disturbances in the OR schedule due to illness of the workforce members, there is a qualitative increase in productivity. Owing to no abrupt cancellation of surgery, the quality is maintained and customer satisfaction is the highest. During the year, given the mathematical calculations of the costs, the plots initially show high-cost. However, for the working year, they attain stable actual values, for example, approximately €350 for 12 ORs.

[37]Note: Cost calculations are based on typical salaries of the workforce in Germany for all the cases but cannot be considered as guiding numbers for planning yet. For precise results, detailed cost data would be needed in future simulation studies. The plots can be used for qualitative purposes.
[38]Note: The values quoted are which simulation achieves at the end of a working year.



(i) Productivity

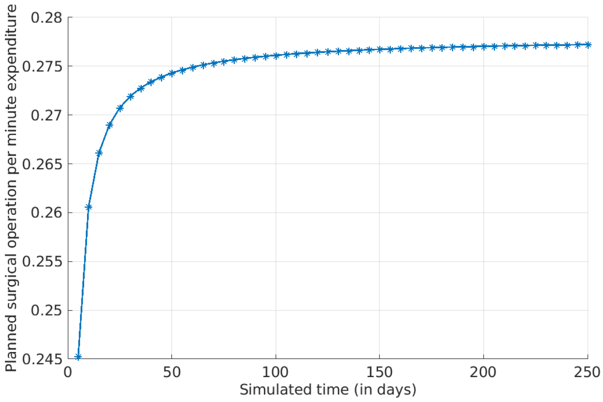
(ii) Quality

(iii) Cost

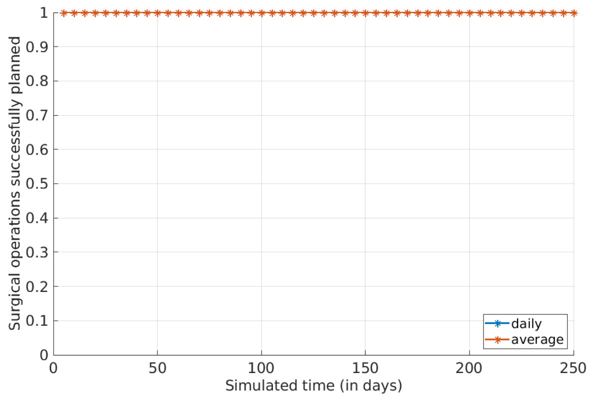
(iv) Cost per day

(v) Customer Satisfaction

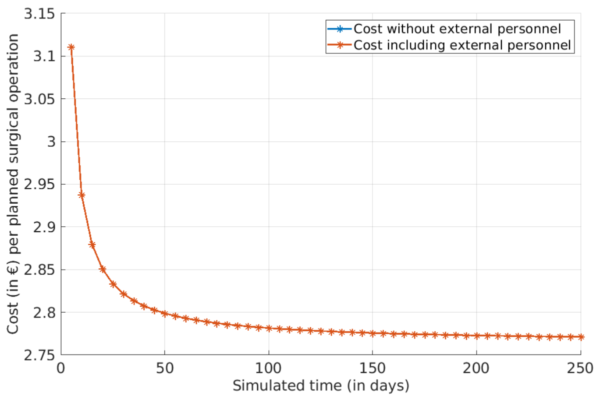
Figure 5.23: Run-sequence plots of an experiment with a total of 12 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist, and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 additional internal personnel per profession and 10 external personnel if the need arises for an OR nurse. The weekly and daily incidents were set to none (0).



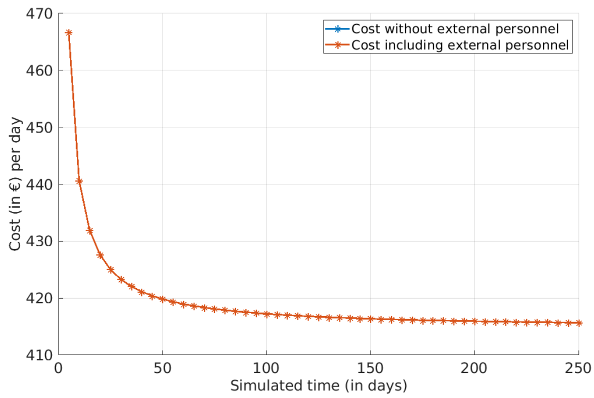
(i) Productivity



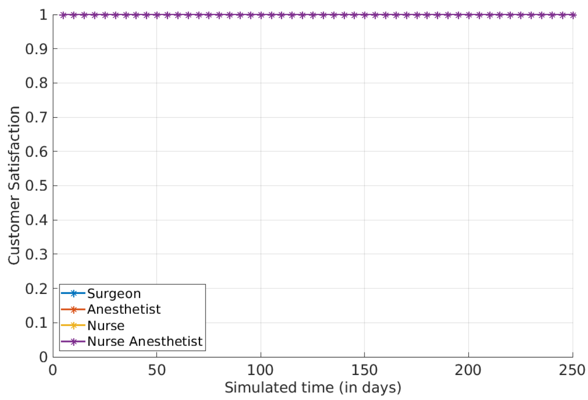
(ii) Quality



(iii) Cost



(iv) Cost per day



(v) Customer Satisfaction

Figure 5.24: Run-sequence plots of an experiment with a total of 15 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist, and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 additional internal personnel per profession and 10 external personnel if the need arises for an OR nurse. The weekly and daily incidents were set to none (0).

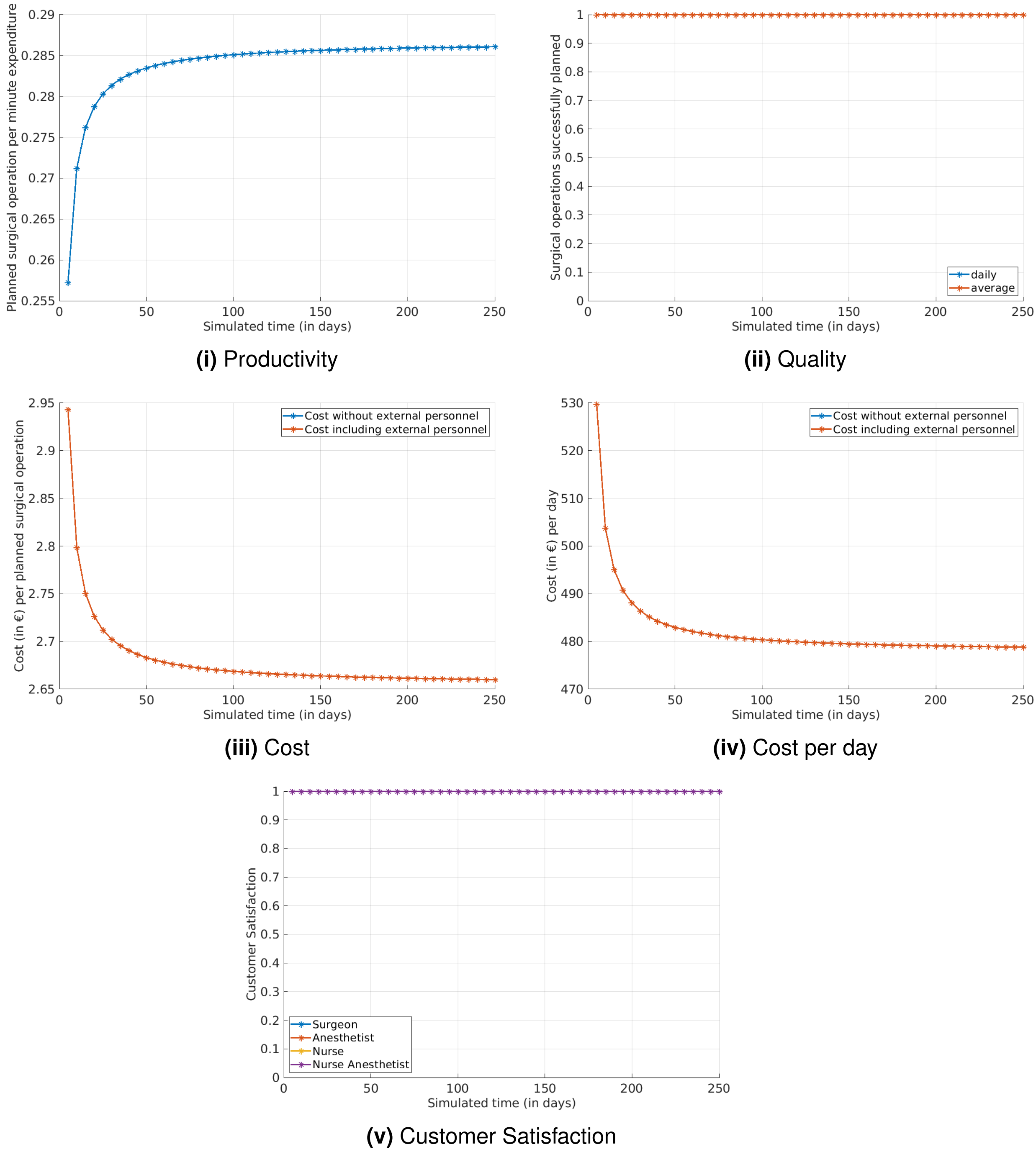
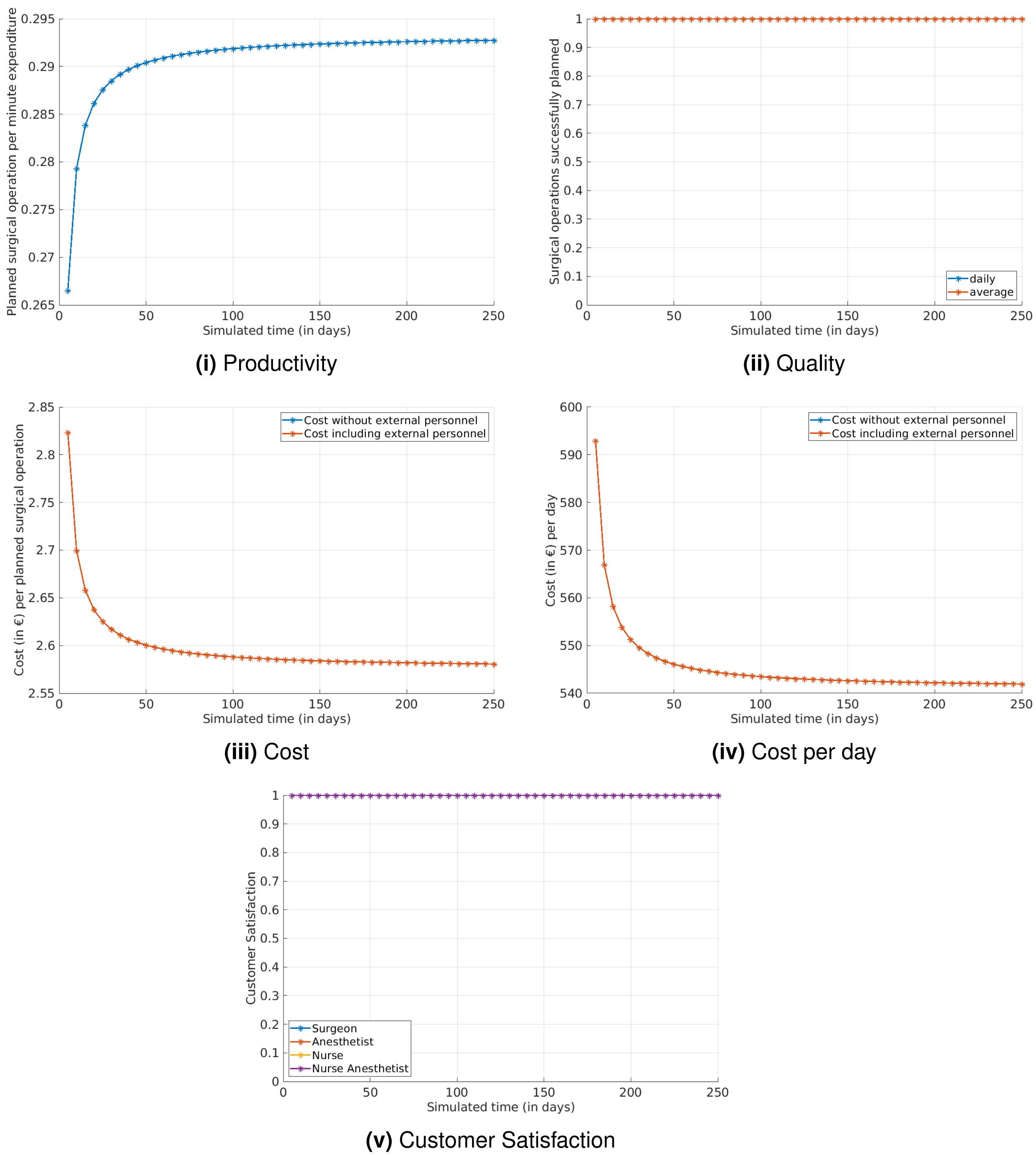


Figure 5.25: Run-sequence plots of an experiment with 15 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist, and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 additional internal personnel per profession and 10 external personnel in case the need arises for an OR nurse. The weekly and daily incidents were set to none (0).



(i) Productivity **(ii)** Quality **(iii)** Cost **(iv)** Cost per day **(v)** Customer Satisfaction

Figure 5.26: Run-sequence plots of an experiment with a total of 21 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 additional internal personnel per profession and 10 external personnel in case the need arises for an OR nurse. The weekly and daily incidents were set to none (0).

5.3.2 Case 2: Keeping as much high-level satisfaction among the workforce

The results exhibited in figures (5.27), (5.28), (5.29), and (5.30) are discussed in this section. The first experiment entailed the simulation of 15 ORs and the outcomes for the entire working year. These are shown in figure (5.27) in terms of productivity, quality, and quality per day. Evidently, case 2-0-2-0 (as defined in the figure caption) results in the least productivity of approximately 0.162. It leads to a quality of 100% owing to the use of externals. It also results in cost of approximately €1500 per day with externals and that of approximately €700 without externals. The increased costs can be attributed to the fact that the external workforce is more costly but can keep ORs running without abrupt cancellations. Further, it is assumed that when we do not use externals, someone steps in as internal workforce to fill in the missing internal workforce. Figure (5.28) shows the simulation results for 2-2-2-2 settings, which implies that apart from average weekly and daily cancellations due to absence of workforce can be up to 2 with variation in the value set to 2 as well. Evidently, in the long term, productivity is shown to drop and the costs shown to rise as compared to case 2-0-2-0. The satisfaction levels remain constant in the case of 2-0-2-0 and 2-2-2-2 cases as we set the initial settings of simulation to high—at a value of five for the satisfaction levels of the workforce. Similarly, two more experimental cases with settings 4-0-4-0 and 4-4-4-4 with 15 ORs but keeping initial satisfaction levels high at five were considered. These experiments sought to investigate the effect of both costs with and without an external workforce. The results are shown in figures (5.29) and (5.30). The plot in figure (5.30) indicates that setting the average cancellation's variation at 4 has the most remarkable effect on the fluctuations in the values of productivity and quality. The cost per day with and without external personnel can be explained. Customer satisfaction of the internal workforce remains constant, as they are replaced with external personnel when needed or with internal employees as well. The OR scheduler or manager can conclude from these four cases that the OR schedule can lead to instability for ORs if the possibility of the replacement of the absent internal personnel with internal skilled workforce is not adequately integrated into the hiring strategy.

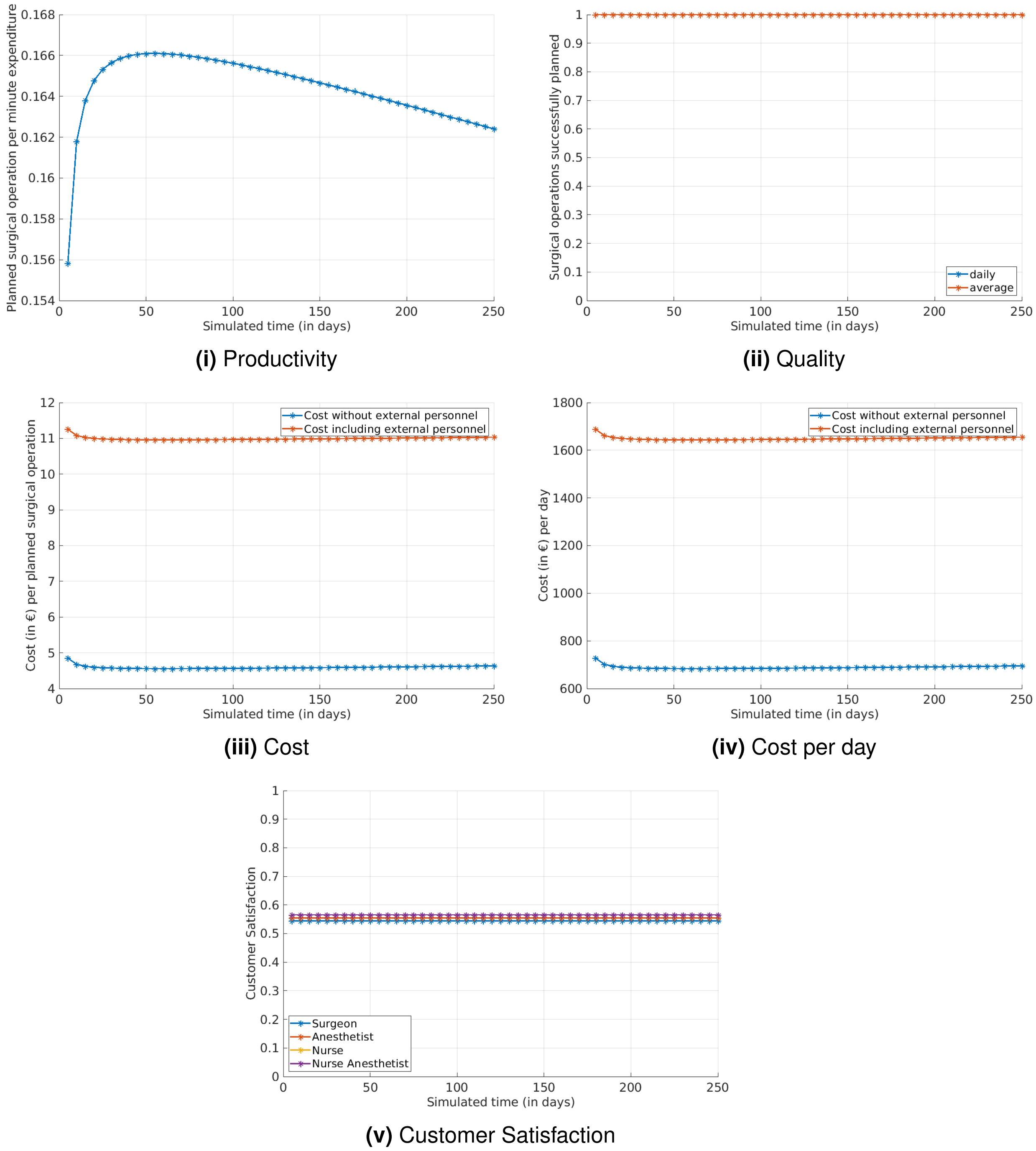
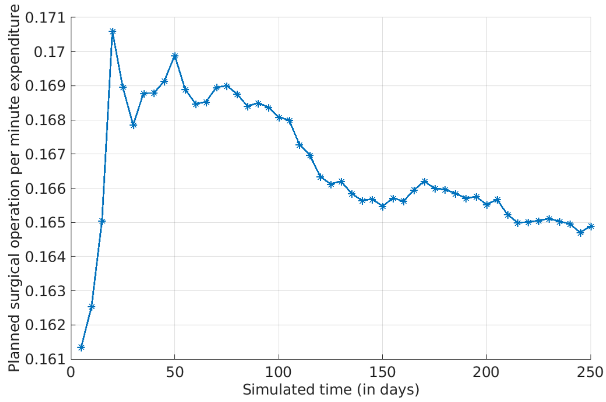
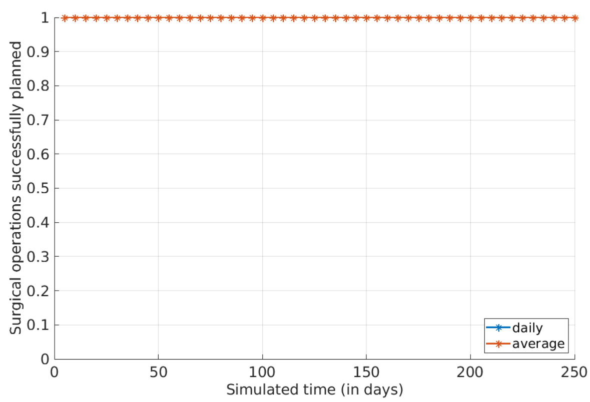


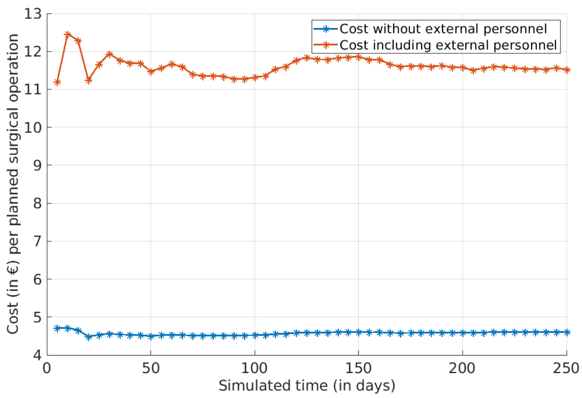
Figure 5.27: Run-sequence plots of an experiment with 15 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 additional internal personnel per profession and 10 external personnel in case the need arises for an OR nurse. The weekly and average daily cancellations were set to 2, whereas the weekly and daily variations of cancellation were again set to none (0).



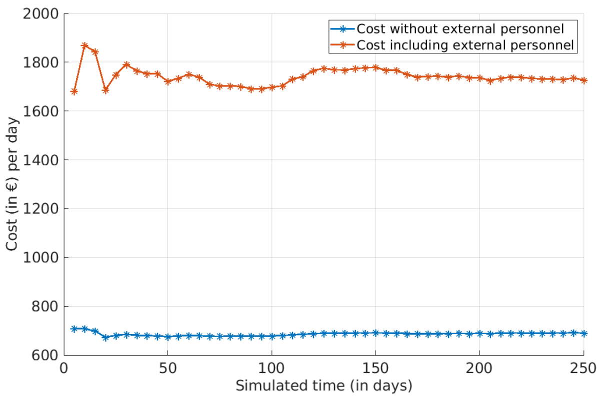
(i) Productivity



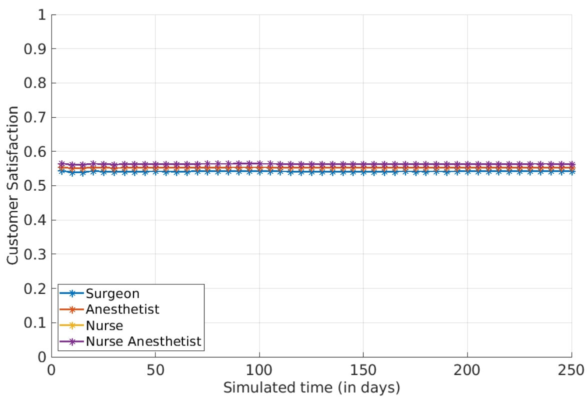
(ii) Quality



(iii) Cost

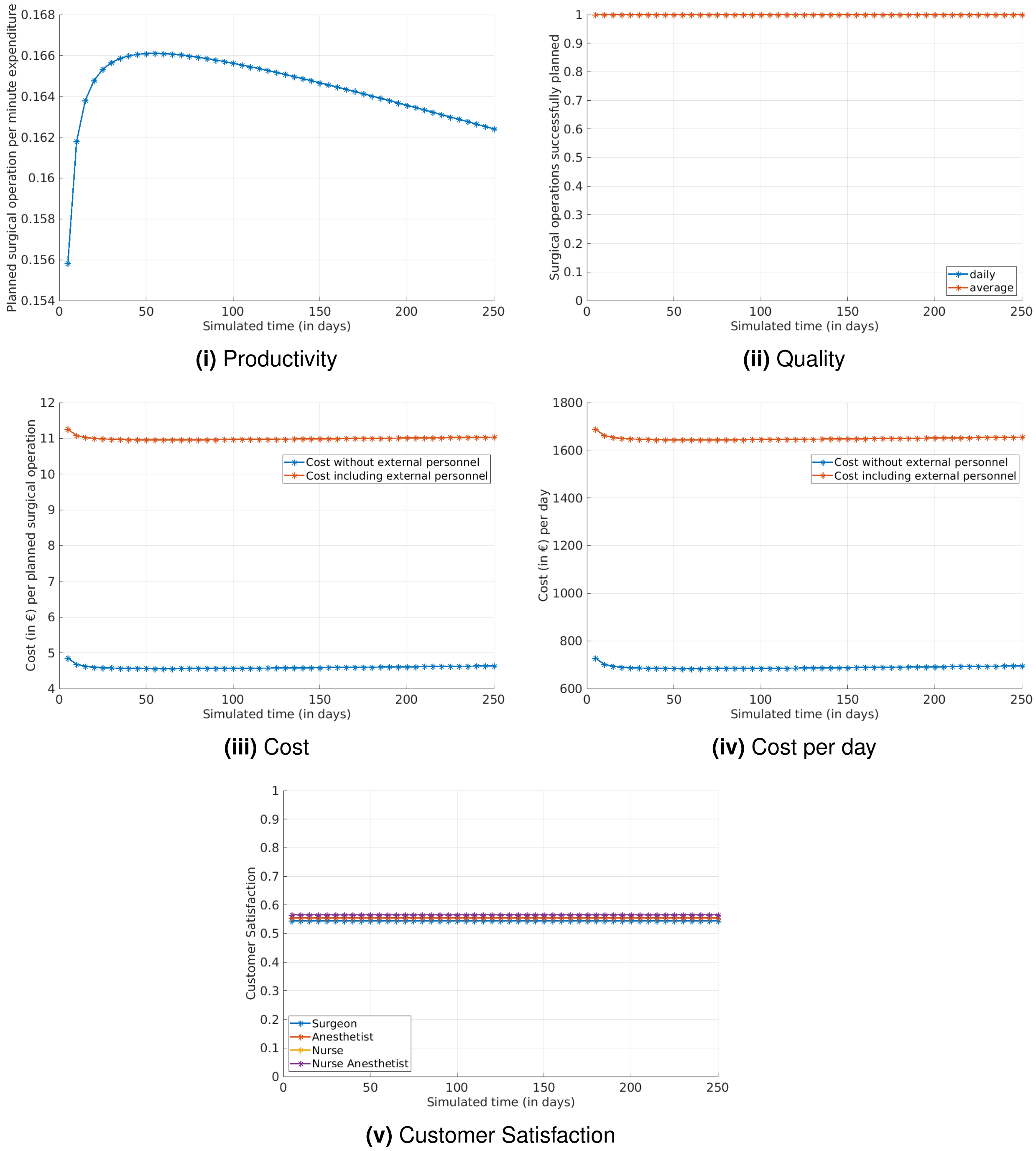


(iv) Cost per day



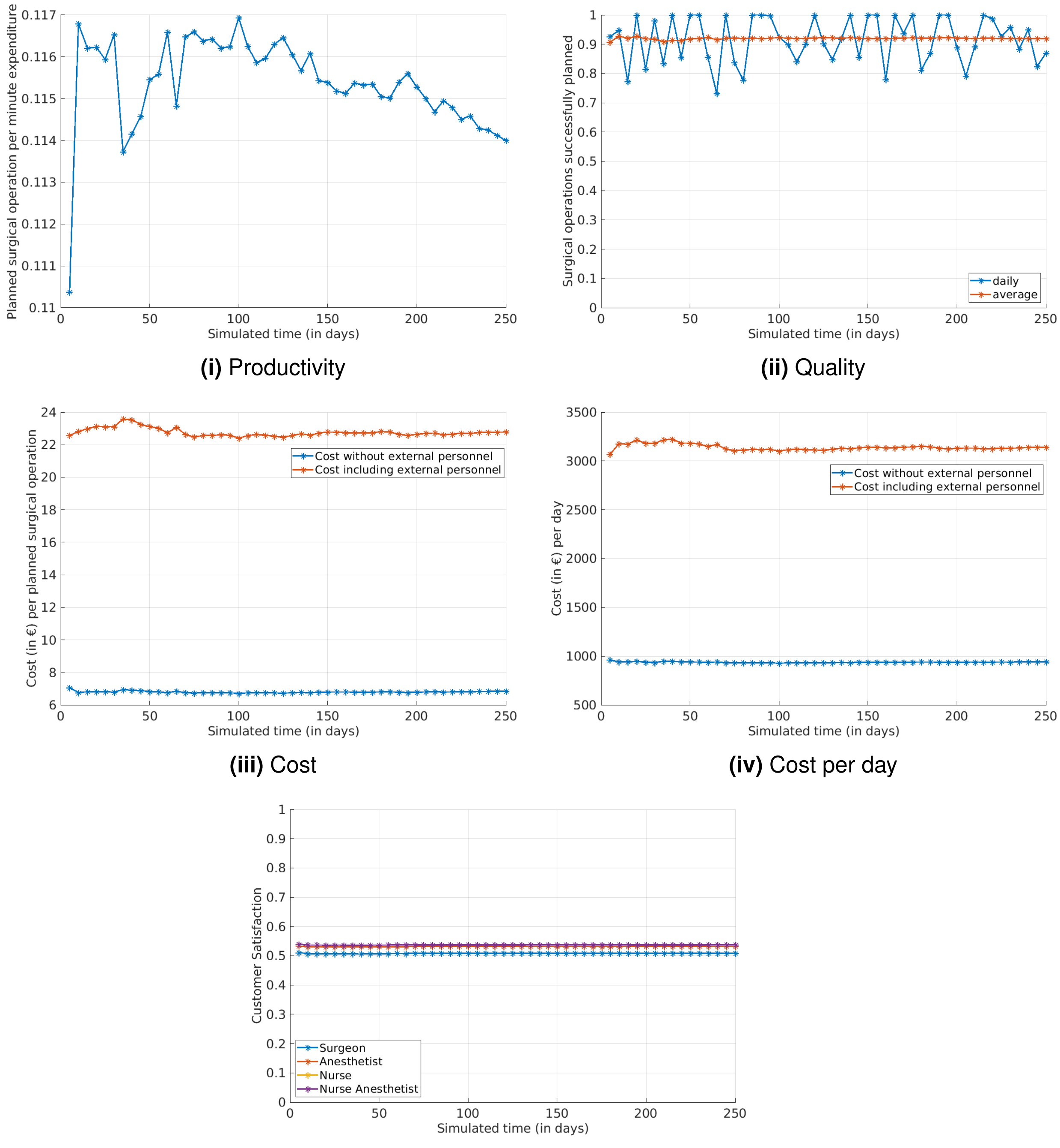
(v) Customer Satisfaction

Figure 5.28: Run-sequence plots of an experiment with 15 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 personnel internal personnel per profession and 10 external personnel if the need arises for an OR nurse. The weekly and daily incidents were set to 2. In addition, the weekly and daily variations of cancellation were again set to 2.



(i) Productivity **(ii)** Quality **(iii)** Cost **(iv)** Cost per day **(v)** Customer Satisfaction

Figure 5.29: Run-sequence plots of an experiment with 15 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 additional internal personnel per profession and 10 external personnel in case the need arises for an OR nurse. The weekly and average daily cancellations were set to 4, whereas the weekly and daily variations of cancellation were again set to none (0).



(i) Productivity

(ii) Quality

(iii) Cost

(iv) Cost per day

(v) Customer Satisfaction

Figure 5.30: Run-sequence plots of an experiment with 15 operating planned rooms with one person for each OR required of type surgeon, OR nurse, anaesthetist and nurse anaesthetist. The personnel can take 30 days per year vacation and manual estimation of satisfaction set at five for all 5 factors. The tolerance is 1 additional internal personnel per profession and 10 external personnel in case the need arises for an OR nurse. The weekly and daily incidents were set to 4.

5.3.3 Case 3: Scheduling with more demand than supply

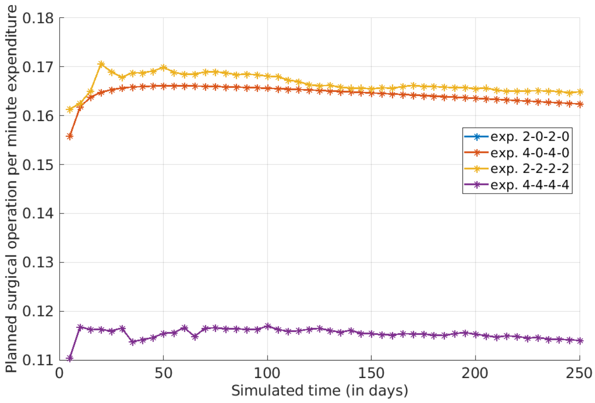
The results shown in figures (5.31), (5.32) and (5.33) are discussed in this section. A case is considered wherein the hypothetical medical care hospital faces an issue when it has surgeries scheduled in its fifteen ORs for the next day. On the day of the planned surgeries, at 7:00, there is a variation in the available workforce due to sudden illness or unplanned absence. The coverage of the ORs is in jeopardy. In this crucial situation, the OR coordinator/scheduler may use ServiceSim OR-WPS for support in decision-making so that they can appropriately run the ORs. The first experiment was run to simulate the outputs of this situation for the whole working year. The results are shown in figure (5.31) in terms of productivity, quality, and quality per day. Evidently, case 4-4-4-4 (as defined in the figure) results in the least productivity, whereas case 2-0-2-0 performs normally and is therefore outside the graph. The quality of case 4-4-4-4 has permanent fluctuations; this is also expected in real life. The four different cost types are shown in figure (5.32) considering with or without external help. Evidently, case 4-4-4-4 results in the least productivity, whereas case 2-0-2-0 performs normal and is therefore outside the graph. The quality of 4-4-4-4 has permanent fluctuations, as is also expected in reality. Similarly, in the same experiment, the customer-satisfaction levels of the process were measured and shown as in figure (5.33). The satisfaction levels are the same for all groups of personnel. The physical explanation of satisfaction level of 0.5 is that the customer is only 50% satisfied. This can be attributed to the computation of satisfaction based on heuristics as described in section (4.2.4.2).

5.3.4 Conclusion of the study

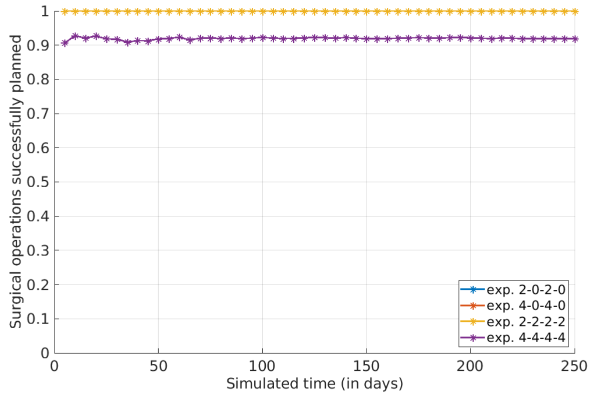
Few conclusions can be drawn based on sections (5.3.1), (5.3.2) and (5.3.3):

(a) If provided with real-world costs and other relevant data, the OR manager and OR coordinator or scheduler can use the ServiceSim OR-WPS multi-agent simulation tool as a DSS to guide strategy development for the ORs. They can validate an OR schedule with extreme resource scenarios and guide the hospital management concept validation together with OR stakeholders.

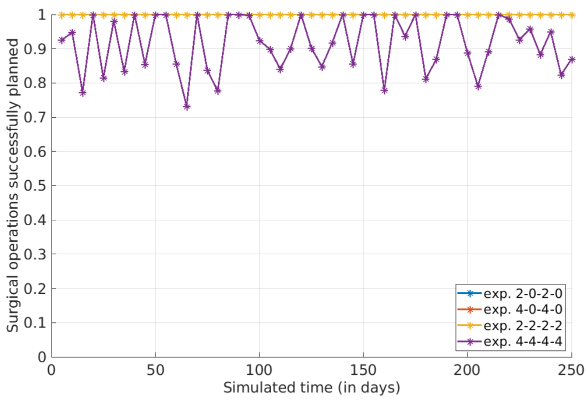
(b) The simulation results demonstrate that the ORs are remarkably dependent on the internal skilled employees if the ORs costs are the main focus of the opti-



(i) Productivity

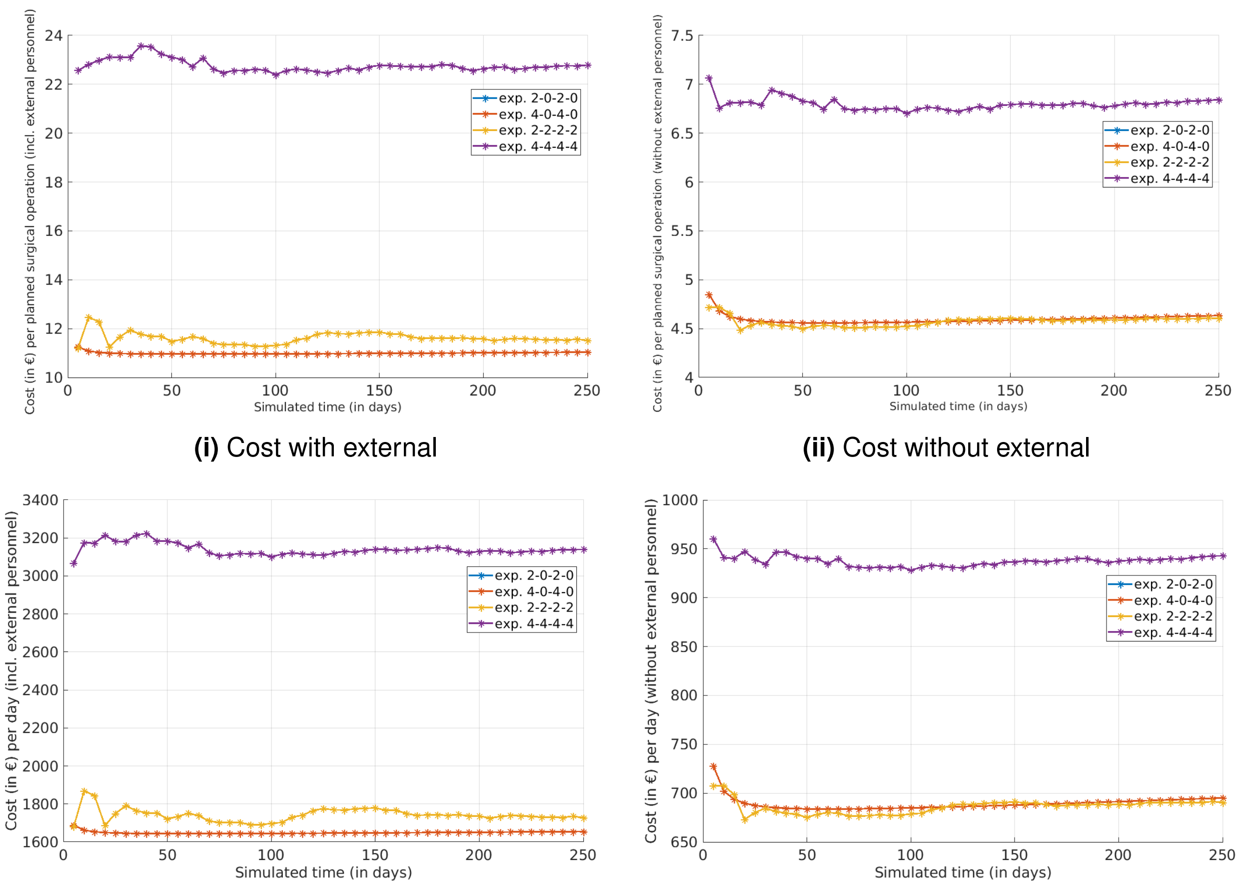


(ii) Quality



(iii) Quality per day

Figure 5.31: Simultaneous run-sequence plots for four experiments illustrating productivity, quality, and quality-per-day for a total of 15 planned operating rooms for surgeries. Each experiment has different settings. The designation "2-0-2-0" of an experiment implies that the person will have 2 weekly average cancellations, 0 weekly variation of cancellation, 2 average daily cancellations and 0 daily variations of cancellation. Similarly, 4-0-4-0, 2-2-2-2, and 4-4-4-4 may be defined.



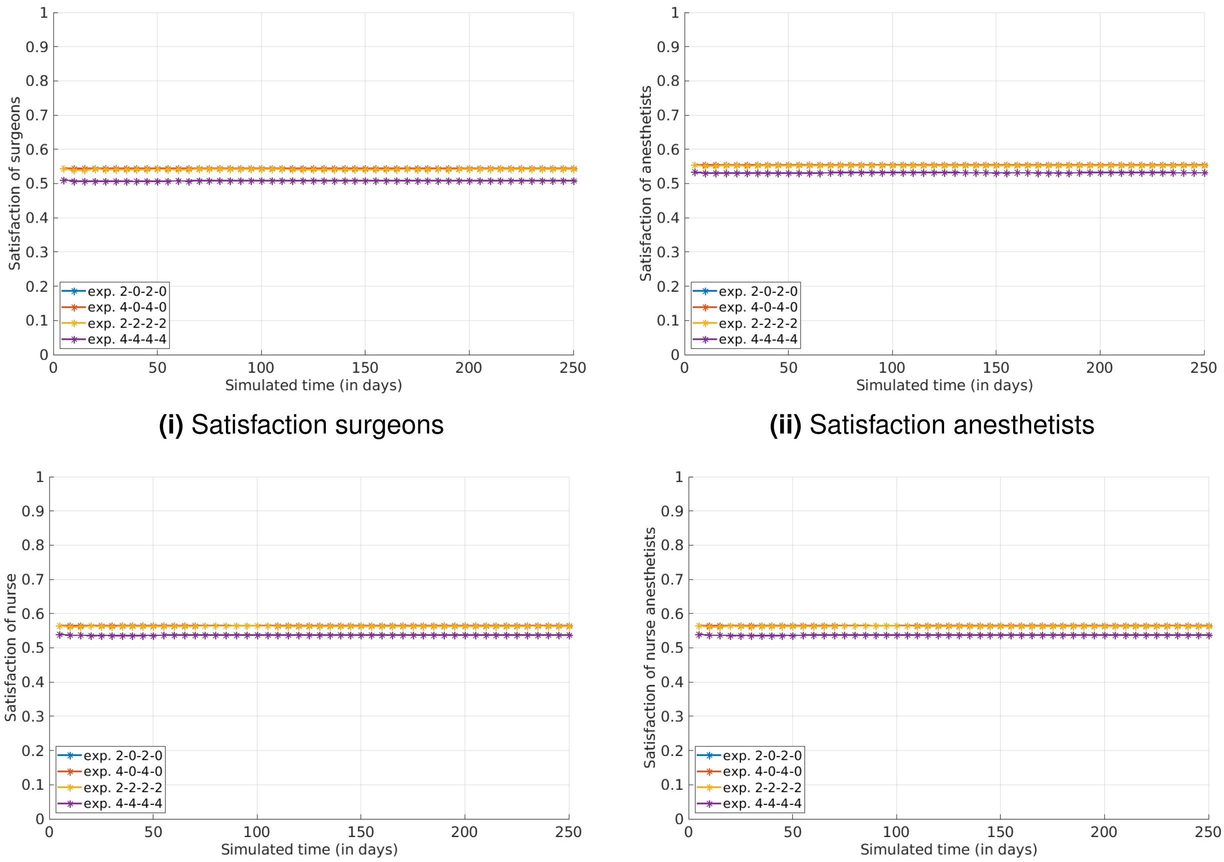
(i) Cost with external

(ii) Cost without external

(iii) Cost per day with external

(iv) Cost per day without external

Figure 5.32: Simultaneous run-sequence plots for four experiments illustrating cost comparisons for a total of 15 planned operating rooms for surgeries. Each experiment has different settings. The designation “2-0-2-0" of an experiment implies that person will have 2 weekly average cancellations, 0 weekly variations of cancellation, 2 average daily cancellations, and 0 daily variations of cancellation. The designations 4-0-4-0, 2-2-2-2, and 4-4-4-4 can be similarly defined.



(i) Satisfaction surgeons

(ii) Satisfaction anesthetists

(iii) Satisfaction nurses

(iv) Satisfaction nurse anesthetists

Figure 5.33: Simultaneous run-sequence plots for four experiments illustrating customer-satisfaction levels for surgeons, anaesthetists, nurses and nurse anaesthetists for a total of 15 planned operating rooms for surgeries. Each experiment has different settings. The designation “2-0-2-0" of an experiment implies that the person would have 2 weekly average cancellations, 0 weekly variations of cancellation, 2 average daily cancellations, and 0 daily variations of cancellation. The designations 4-0-4-0, 2-2-2-2, and 4-4-4-4 are similarly defined.

mization. If an external workforce is part of corporate hospital strategy, whether this works in healthcare surgical operations can be tested and validated.

5.3.5 Advantage and limitation of the study

The primary advantages in applying multi-agent modelling and simulation on OR-WPS are as follows:

(a) Hospitals can use the ServiceSim OR-WPS tool to experiment in a safe environment without interrupting the current operations in the hospitals and validate what-if scenarios upfront before realization.

(b) The simulation tool is scalable; with appropriate modifications in the logical part of the program, multiple hospitals can be considered. Moreover, it can even simulate the ORs situation of the total healthcare system of a country. It can be realised either as a one-hospital simulation or parallel simulations of hundreds of independent hospital simulations with aggregation before the results are reported.

During the multi-agent modelling and simulation in this study, the following limitations were noted:

(a) All computer models of entities/processes/dynamic behaviours approximate what can be observed and experienced in reality. Given this fundamental nature of computer models, such as multi-agent/discrete-event/system-dynamics models, they have inherent errors due to approximation. If the errors are known and within limits, the models are acceptable. The multi-agent model for OR-WPS has the same errors owing to its design; these errors can be limited and warrants further investigation.

(b) Given the scope of the study, only a limited number of initial conditions for the computer simulation were considered in the experiments. The initial condition can significantly affect the outcome of an experiment. A well-known example similar to this aspect is from *chaos theory*, known as the *butterfly effect*[39]. It is

[39] Butterfly Effect, http://www.cmp.caltech.edu/~mcc/chaos_new/Lorenz.html

widely cited in the context of weather phenomena than in business process simulation. Either a multitude of experiments or suitable experiment design could address these effects in future research.

5.4 Quantitative Study in OR-WPS Process Area

In order to perform work sampling at the UMHS, the following samples for Nurse Scheduler, Nurse Anaesthetist, and Anaesthesiologist, as shown in table (5.4), were *randomly* collected in 29 days for an equivalent of 222 working hours. Based on 99% confidence and 10% accuracy and a preliminary estimate of the percentage of time spent on the significant activity of P = 15%, the collected samples should be equal to or more than 3066 counts. All three categories of samples qualify this criterion as shown in table (5.4) with 4513, 3180, and 3192 samples for Nurse Scheduler, Nurse Anaesthetist, and Anaesthesiologist, respectively. For further details, the tables for sample size with 90%, 95% and 99% provided by Aft[40,41] may be referred to. Figure (5.34) depicts a distribution of various activities as shown in tables (5.5) and (5.6) conducted by nurse schedulers shadowed during work sampling data collection. In the case of nurse schedulers, one can infer that they spend their working days performing activities to support the OR-WPS enabling process. The top five categories[42] of the activities of the nurse schedulers are as follows:

(a) To discuss staffing with their nursing colleagues (cat. 27)

(b) Walk from one area of OR to another (cat. 52)

(c) Prepare weekly staffing schedule (cat. 45)

(d) Sending and receiving messages via pager, computer, and phone (cat. 30)

(e) Participate in the OR board runner and huddle meetings (cat. 44)

In contrast, as exhibited in figure (5.35), which corresponds to various activities as shown in tables (5.5) and (5.6) conducted by nurse anaesthetist schedulers shadowed during work sampling data collection, they are focused on different ones. In the case

[40]Source: Ibid - Aft (2000) [Aft00, pp. 303-305]

[41]Note: The z value for 99% confidence is equal to 2.575. The 99% confidence means that we are 99% much confident that the samples will contain the actual population.

[42]Note: The term *category* is abbreviated as *cat.*.

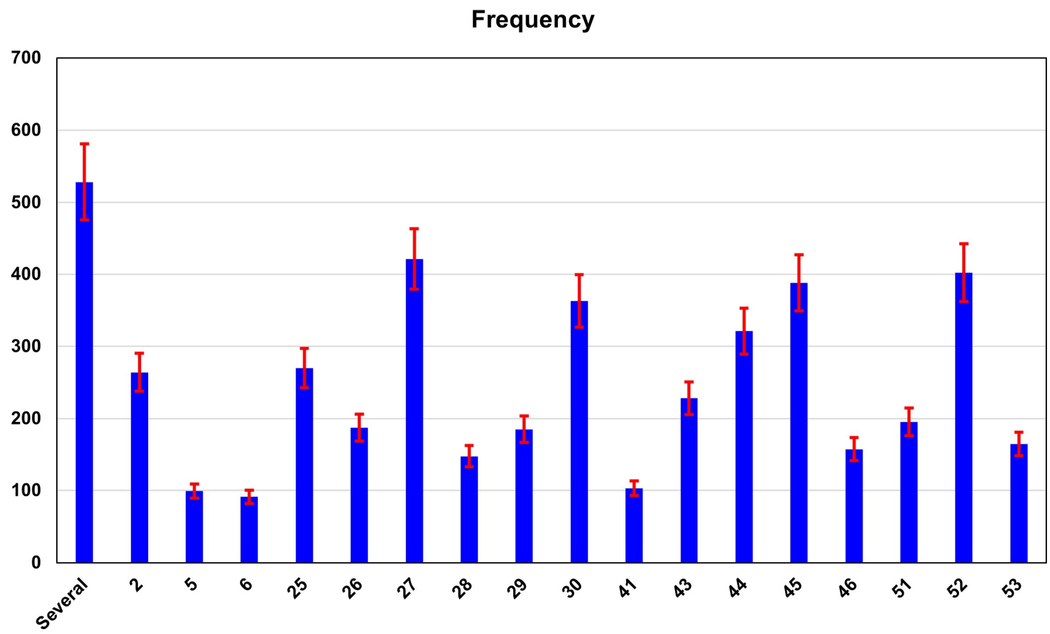


Figure 5.34: A histogram for nurse schedulers' share of work activity categories in absolute numbers and 10% error based on work sampling in the OR-WPS process area. Categories 1, 3, 4, 7, 8, 9, 10, 11, 12, 21, 22, 23, 24, 31, and 42 were combined and called "Several" category owing to an extremely low share—less than ($\lesssim$ 1.5%)

Profession	*Topic*	*Values*
Nurse scheduler	Time duration Shift Time covered **Sample size**	Sept-Oct,15 Morning-Afternoon 98 hours or 13 days **4513**
Nurse anaesthetist scheduler	Time duration Shift Time covered **Sample size**	Oct,15 Morning-Afternoon 63 hours or 8 days **3180**
Anaesthesiologist scheduler	Time duration Shift Time covered **Sample size**	Sept-Oct,15 Morning-Afternoon 61 hours or 8 days **3192**
	Grand total time covered	222 hours or 29 days
	Grand total sample size	**10885**

Table 5.4: An overview of the duration and sample collected of different roles in OR-WPS at UMHS

of nurse anaesthetist schedulers, it was found that they spend their working days performing activities that are in the descending order of occurrence:

(a) Self-working in OR (cat. 7)

(b) Performing talks with colleagues about the case (cat. 51)

(c) Walk from one end to another OR (cat. 52)

(d) Self-checking patients in the staging area (cat. 6)

(e) Check e-mail on human resource software (cat. 28)

In contrast, as exhibited in figure (5.36), which corresponds to various activities as shown in tables (5.5) and (5.6) conducted by anaesthesiologist schedulers shadowed during work sampling data collection, they are again focused on different ones. In the case of anaesthesiologist schedulers, it was found that they spend their working days performing activities that are in the descending order of occurrence:

(a) Self-working in OR (cat. 7)

(b) Walking from one area of OR to another (cat. 52)

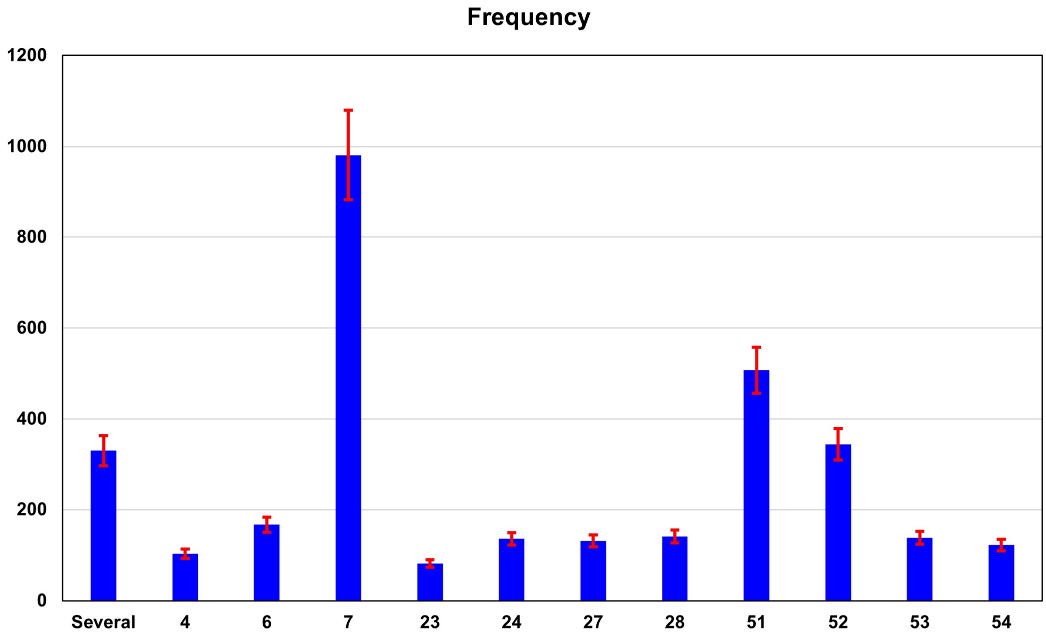


Figure 5.35: A histogram for nurse anaesthetist schedulers' share of work activity categories in absolute numbers and 10% error based on work sampling in the OR-WPS process area. Categories 1, 2, 3, 5, 8, 21, 22, 25, 26, 29, 30, 41, 42, 43, and 45 were combined and called "Several" category owing to the extremely low share ($\lesssim$ 1.5%)

(c) Self-checking patients in the staging area (cat. 6)

(d) Case tracking on the OR display (cat. 29)

(e) Prepare weekly staffing schedule (cat. 45)

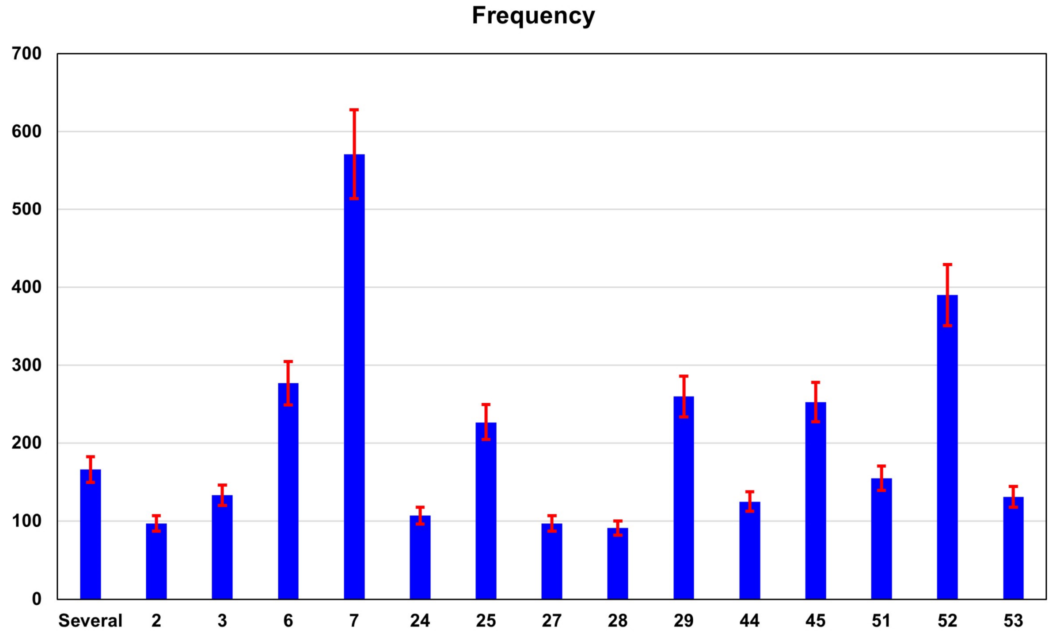


Figure 5.36: A histogram for anaesthesiologist schedulers' share of work activity categories in absolute numbers and 10% error based on work sampling in the OR-WPS process area. Categories 1, 4, 5, 8, 21, 22, 23, 26, 30, 41, 42, and 43 were combined and called "Several" category owing to the extremely low share ($\lesssim$ 1.5%)

Another type of illustration of the same work sampling data collected could be a pie chart showing a share of activities to support the OR-WPS enabling process. In figure (5.37), the data shown in figure (5.34) is represented as a pie chart. The top five activities of a nurse schedulers are as follows:

(a) To discuss staffing with their nursing colleagues (cat. 27 at 9.33%)

(b) Walk from one area of OR to another (cat. 52 at 8.91%)

(c) Prepare weekly staffing schedule (cat. 45 at 8.60%)

(d) Sending/receiving messages via pager, computer and phone (cat. 30 at 8.04%)

CT.	*Description*	*Nur.*	*Nur.Ana.*	*Anaesth.*
1	Check-up on OR availability	✓	✓	✓
2	Check-up with Nursing OR Board Runner/Unit Clerk	✓	✓	✓
3	Check-up on Surgeons, Anaesthesiologists and Residents	✓	✓	✓
4	Check-up on Nurse Anaesthetist availability	✓	✓	✓
5	Check-up on material availability	✓		
5	Add-on case staff scheduling		✓	✓
6	Cases moved from one OR to another	✓		
6	Self checking patient at staging area		✓	✓
7	Add-on case staff scheduling	✓		
7	Self working in OR		✓	✓
8	Stretcher stripping	✓		
8	Patient (pain management) rounding		✓	✓
9	Self working / nursing help	✓		
10	Staffing issue due to residents	✓	✓	✓
11	Opening (additional) OR room	✓		
12	Staffing issue due to lunch / breaks	✓	✓	✓
21	Check for patient availability	✓	✓	✓
22	On phone for blood request	✓		
22	Writing on board breaks and lunch		✓	✓
23	On phone for supplies	✓		
23	Writing on board for staff schedule		✓	✓
24	On pager to read message	✓		
24	Discuss staffing with colleagues		✓	✓
25	Writing on board breaks and lunch	✓		
25	Discuss (medical) issues with colleagues		✓	✓
26	Writing on board for staff schedule	✓		
26	Check e-mail or Human Resource software		✓	✓
27	Discuss staffing with colleagues	✓	✓	✓
28	Check e-mail or Human Resource software	✓	✓	✓
29	Case tracking on OR display	✓	✓	✓
30	Sending/receiving messages via pager, computer and phone	✓	✓	✓
31	Late OR start reporting	✓		

Table 5.5: Part (1): Categories (CT.) of the observational work sampling through job-shadowing the nursing staff scheduler (Nur.), nurse anaesthetist scheduler (Nur. Ana.), and anaesthesiologist scheduler(Anaesth.).

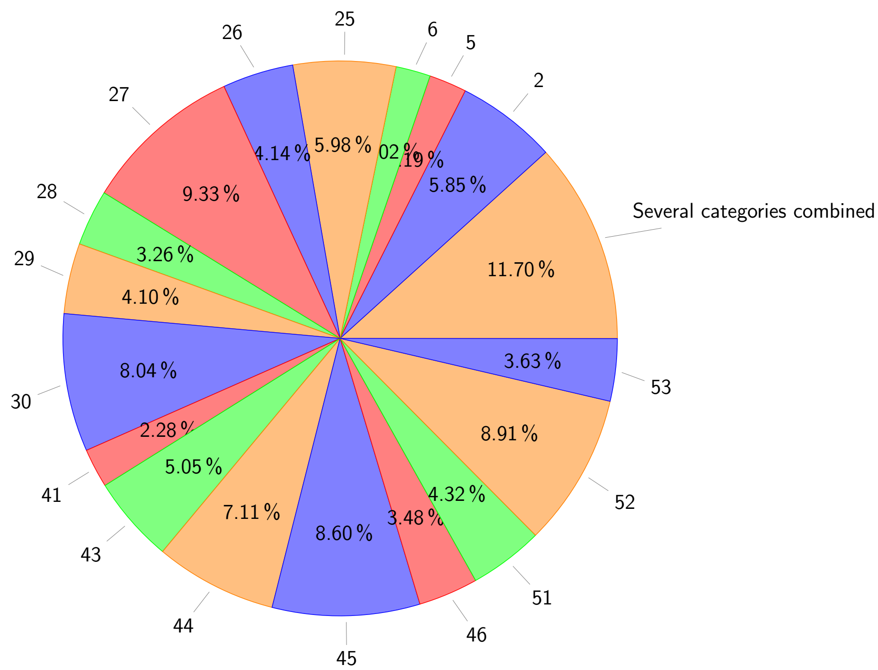


Figure 5.37: A pie chart shows the share of work activity categories in percentage based on work sampling for *nurse schedulers* in the OR-WPS process area. Categories 1, 3, 4, 7, 8, 9, 10, 11, 12, 21, 22, 23, 24, 31, and 42 were combined and called "Several categories combined" due to the considerably low share ($\lesssim$ 1.5). The two partially hidden values are for categories 5 and 6; these are 2.19 and 2.02, respectively.

CT.	Description	Nur.	Nur.Ana.	Anaesth.
41	Helping with first OR start	✓		
41	Helping to supply the material and pharmacy		✓	✓
42	Helping to supply the material	✓		
42	Arrange equipment and material in OR		✓	✓
43	Arrange equipment and material	✓		
43	Transporting patient		✓	✓
44	Rounding with nursing staff	✓		
44	OR board runner and huddle meeting		✓	✓
45	OR board runner and huddle meeting	✓		
45	Prepare weekly staffing schedule		✓	✓
46	Prepare weekly staffing schedule	✓		
51	Relaxing (coffee, wash-room, small-talk)	✓	✓	✓
52	Walking	✓	✓	✓
53	Lunch break for self	✓	✓	✓
54	Others (filled survey or discussion)		✓	✓

Table 5.6: Part (2): Categories (CT.) of the observational work sampling through job-shadowing the nursing staff scheduler (Nur.), nurse anaesthetist scheduler (Nur. Ana.), and anaesthesiologist scheduler(Anaesth.).

(e) To participate in the OR board runner and huddle meetings (cat. 44 at 7.11%).

Similarly, as shown in figure (5.39), in the case of nurse anaesthetist schedulers, it was found that they spend their working days performing activities that are in the descending order of occurrence:

(a) Self-working in OR (cat. 7 at 17.91%)

(b) Performing talks with colleagues about the case (cat. 51 at 15.94%)

(c) Walk from one end to another OR (cat. 52 at 10.79%)

(d) Self-checking patients in the staging area (cat. 6 at 5.25%)

(e) Check e-mail on human resource software (cat. 28 at 4.43%)

As do the nurse anaesthetists, the anaesthesiologist schedulers perform similar activities. These are shown in figure (5.39), in descending order of occurrence and correspond to various activities as shown in tables (5.5) and (5.6):

(a) Self-working in OR (cat. 7 at 17.91%)

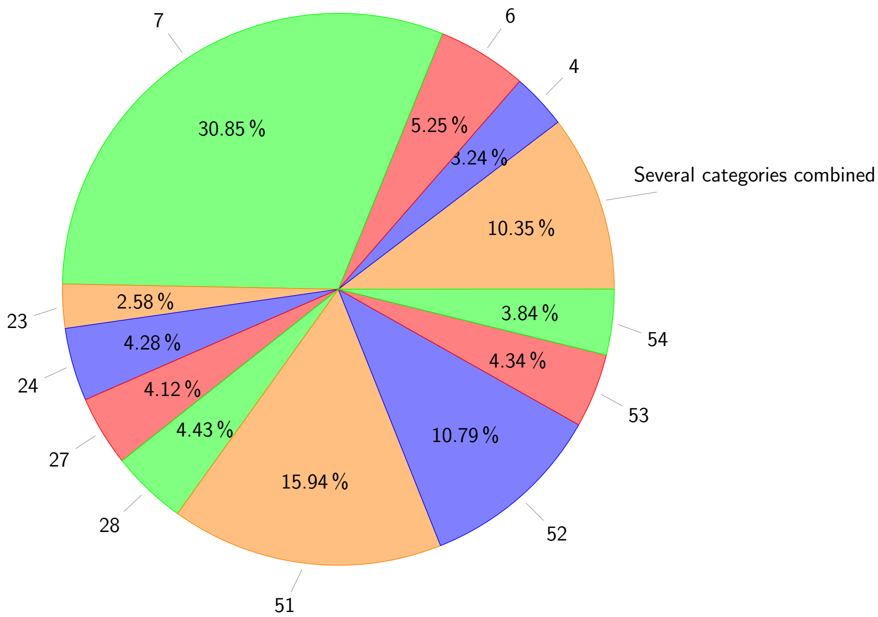


Figure 5.38: A pie chart illustrates the share of work activity categories in percentage based on work sampling for *nurse anaesthetist schedulers* in the OR-WPS process area. Categories 1, 2, 3, 5, 8, 21, 22, 25, 26, 29, 30, 41, 42, 43, 44, 45 were combined and called “Several categories combined" owing to the extremely low share ($\lesssim$ 1.5). One partially hidden value for category 4 in the figure is 3.24.

(b) Walking from one area of OR to another (cat. 52 at 12.22%)

(c) Self-checking patients in the staging area (cat. 6 at 8.71%)

(d) Case tracking on the OR display (cat. 29 at 8.14%)

(e) Prepare weekly staffing schedule (cat. 45 at 7.91%)

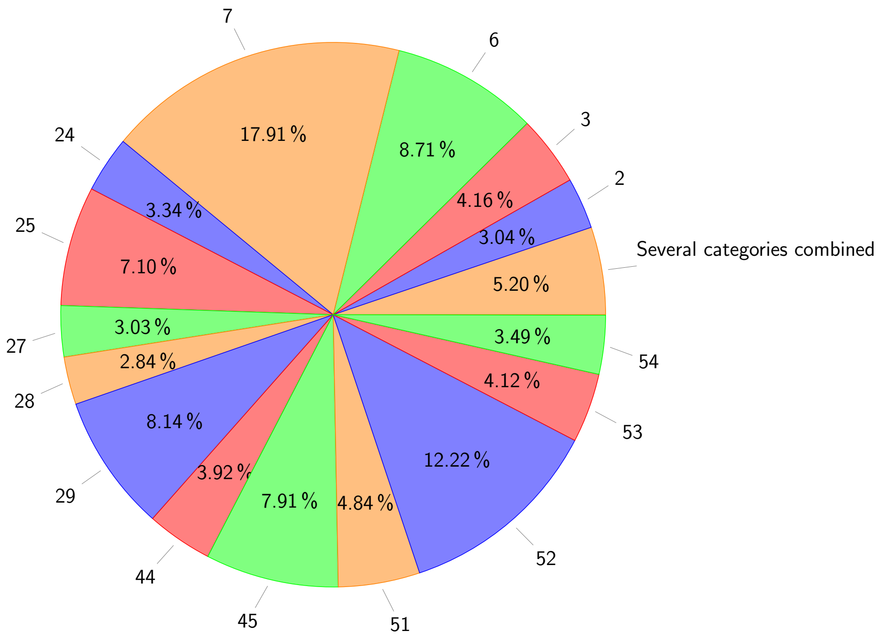


Figure 5.39: A pie chart illustrates the share of work activity categories in percentage based on work sampling for *anaesthesiologist schedulers* in the OR-WPS process area. Categories 1, 4, 5, 8, 21, 22, 23, 26, 30, 41, 42, and 43 were combined and called "Several categories combined" owing to the remarkably low share ($\lesssim$ 1.5).

The histograms for the nurse, nurse anaesthetist, and anaesthesiologist, as shown in figures (5.34), (5.35), (5.36), respectively, provide cumulated information during the work sampling exercise but are not necessarily helpful in creating random inputs for a computer simulation needed to specify a probability distribution function[43]. Here, randomness implies that all the physical phenomena exhibit randomnesses such as the arrival of patients to the hospital or a meteor falling on the earth. As indicated by the previously stated RQs, one of the objectives of the work sampling exercise

[43]Source: Averill M. Law (2011), How to select simulation probability distribution [Law]

was to determine the probability distribution function based on the data collected at UMHS. It is essential to avoid any pitfalls mentioned by Law[44], such as in replacing a distribution with the mean or using a wrong distribution function. In this study, specific attention is on the type of probability distribution to be selected in the beginning and why it would be suitable for multi-agent simulation of the OR-WPS process or any discrete event in general. As regards the empirical data collected by observing various roles (nurse scheduler, nurse anaesthetist scheduler, and anaesthesiologist scheduler), the general family of distribution functions such as exponential, gamma, Weibull, normal or log-normal may be selected for fitting. A test plot of a category of activity was obtained using the data collected during the sampling; this plot showed a behaviour of normal distribution, provided the sample data had sufficient data points to (correctly) calculate the distribution parameters. It is a recommended practice in a computer simulation that if a *standard theoretical distribution* represents the empirical data collected, using the standard is the best approach in the beginning[45]. A plot of normal distribution curve with mean $\overline{x} = 0$ and standard deviation σ based on equation (5.2) is as shown in figure (5.40).

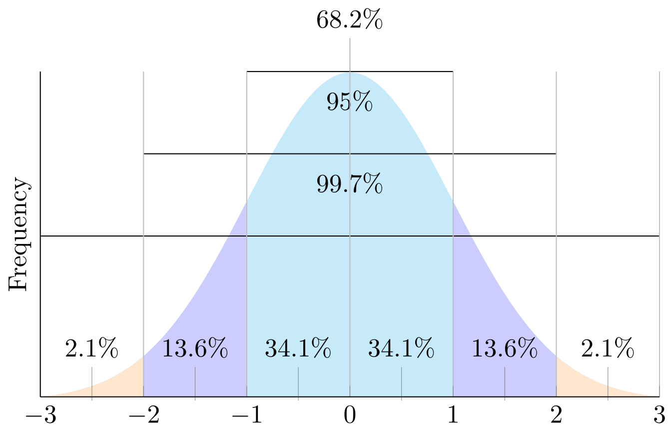


Figure 5.40: Curve of normal distribution

On the basis of the foregoing explanation, as the selected distribution is expected, the *distribution parameters*[46] used in the computer simulation can be estimated as

[44]Source: Ibid - Law (2011)

[45]Note: In the absence of sufficient sample data points, the standard parameters of the distribution, such as mean and standard deviation, cannot be calculated. Hence, the distribution cannot be found.

[46]Note: An example from exponential distribution is a β.

follows. According to Law, the maximum-likelihood estimators (MLE)[47] can be calculated using a sample of observed data; this is expressed as equation (5.1).

$$\boxed{L(\theta) = f_\theta(x_1) f_\theta(x_2) \dots f_\theta(x_n)} \tag{5.1}$$

where

L(θ) = Joint probability density function for an unknown parameter θ
x = Observed data during work sampling

The sample data were used to calculate the parameters. The mean $\overline{x}$ of the observations for different days was calculated along with the standard deviation σ of the mean, as shown in equation (5.2).

$$\boxed{\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \overline{x})^2}} \tag{5.2}$$

where:

σ = Standard deviation
N = Number of days observed
x_i = Counts of activities on each day
$\overline{x}$ = Mean of the observed value of all days

Not all the collected datasets for OR-WPS during work sampling would fit the selected theoretical distribution function, namely, a normal distribution. This can be because of the lack of a sufficient number of observed data. Thus, the goal was to determine and fit the distribution sufficiently close to the intended purpose of providing input to the computer simulation with random distribution data.

5.4.1 Conclusion of the study

These conclusions can be made based on figures (5.37), (5.38), (5.39), (5.41), (5.42), (5.43), (5.44), (5.45), (5.46), (5.47) and (5.48):

(a) The share of work activities as in figures (5.37), (5.38), (5.39) can be practically used for improvement purposes. To this end, one must determine the reason

[47] Source: For more details - Averill M. Law (2007), Simulation and modeling [Law07]

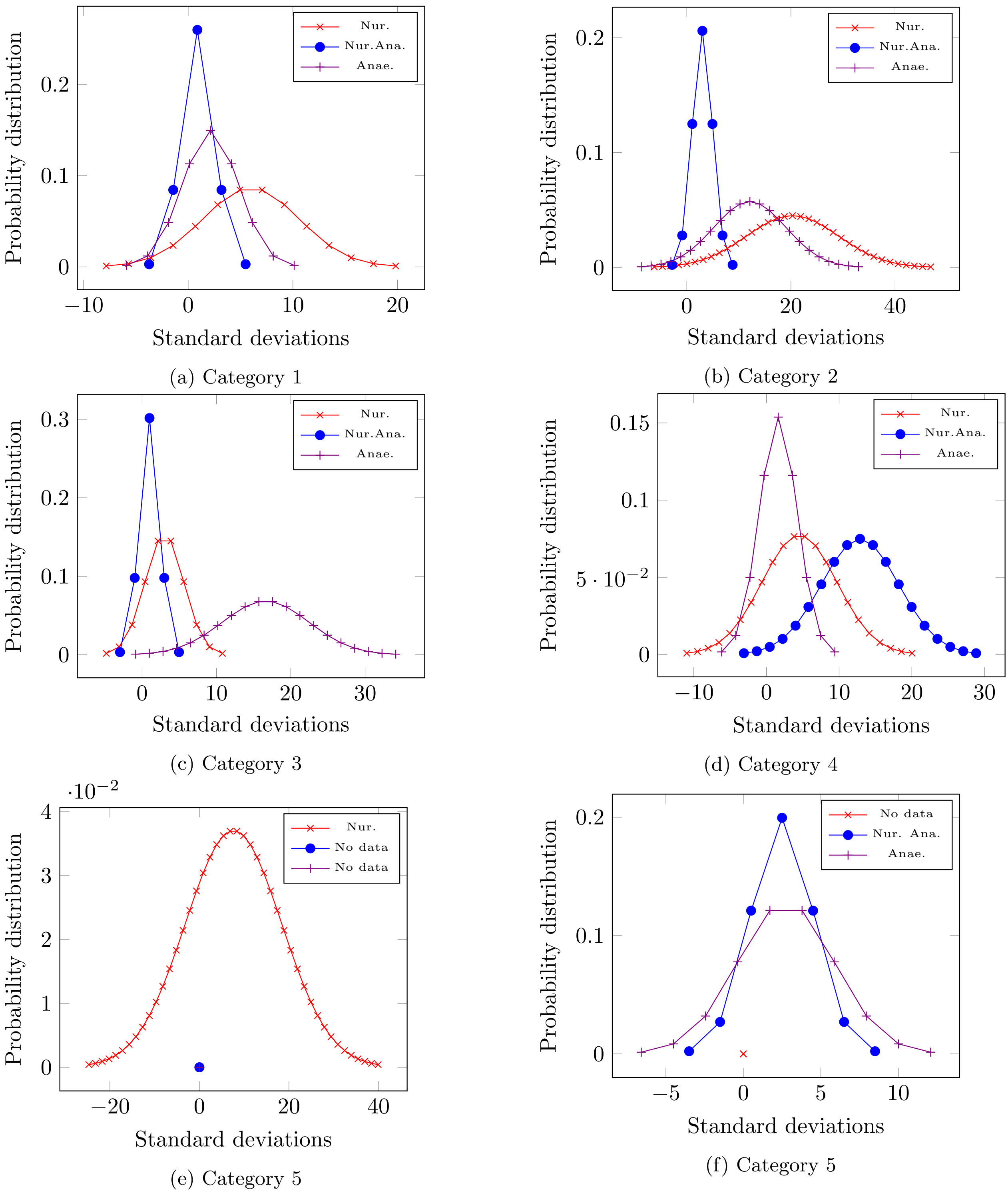
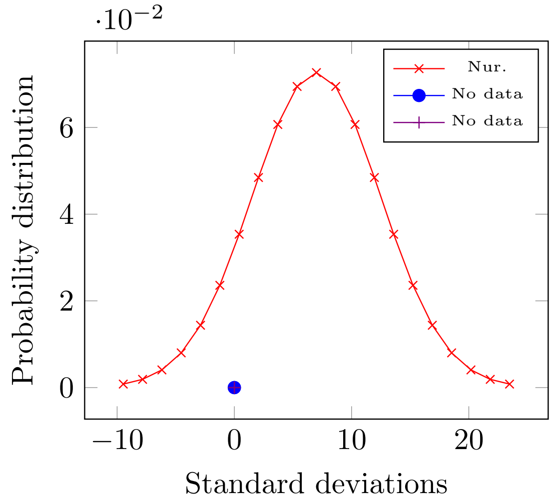
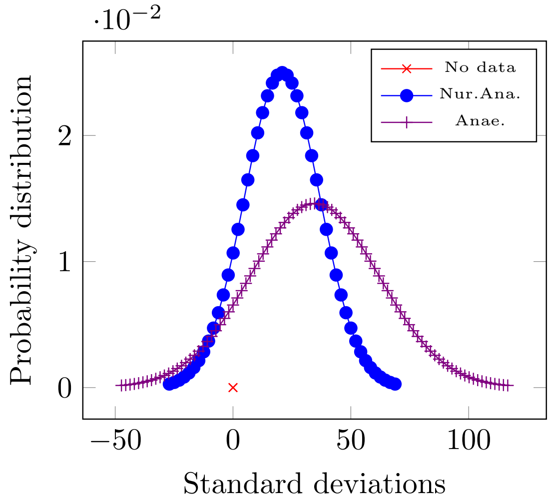


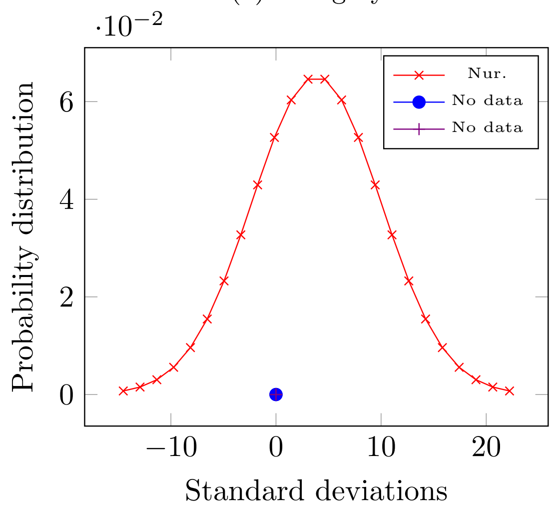
Figure 5.41: 1st set of plots of normal distribution function for the nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling



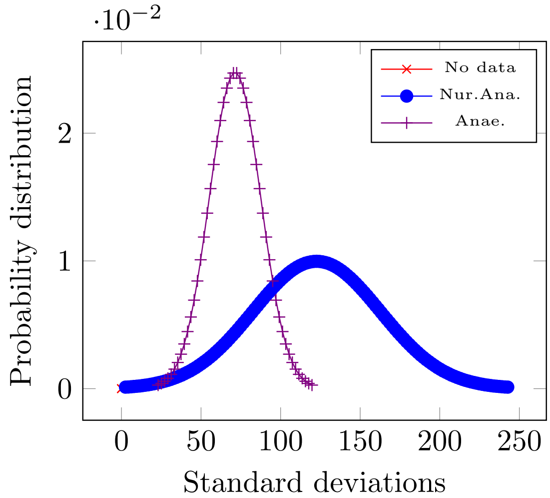
(a) Category 6



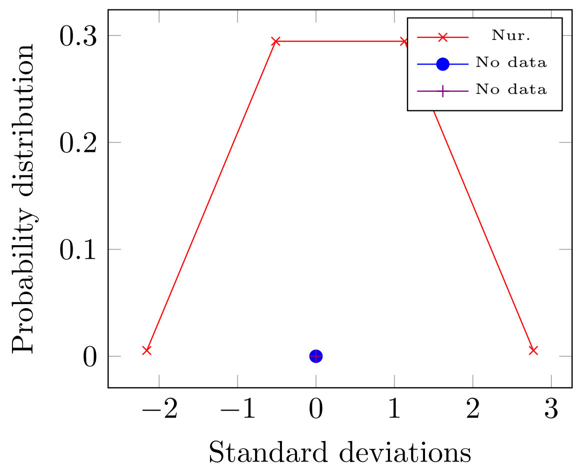
(b) Category 6



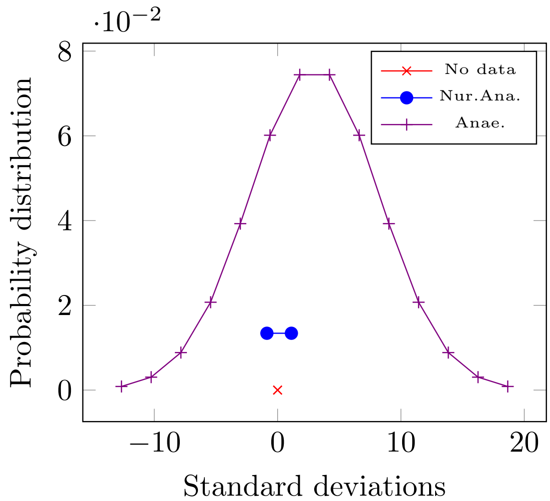
(c) Category 7



(d) Category 7

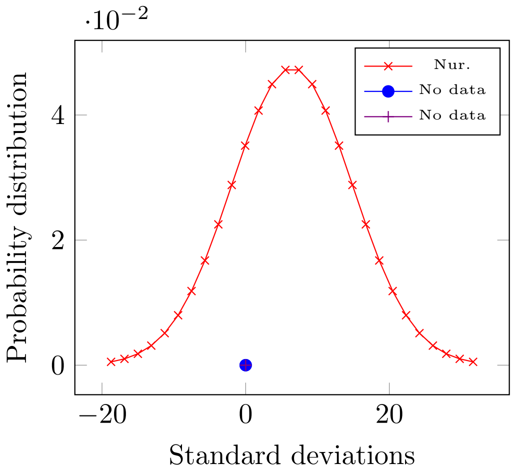


(e) Category 8

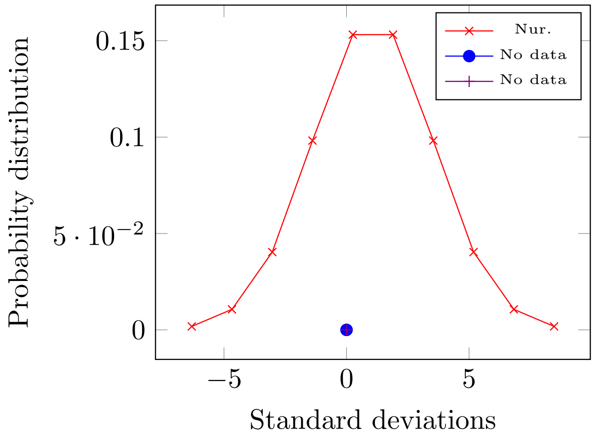


(f) Category 8

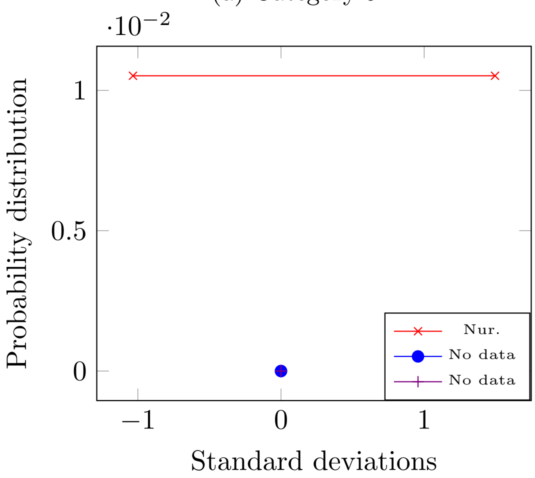
Figure 5.42: 2nd set of plots of normal distribution function for nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling



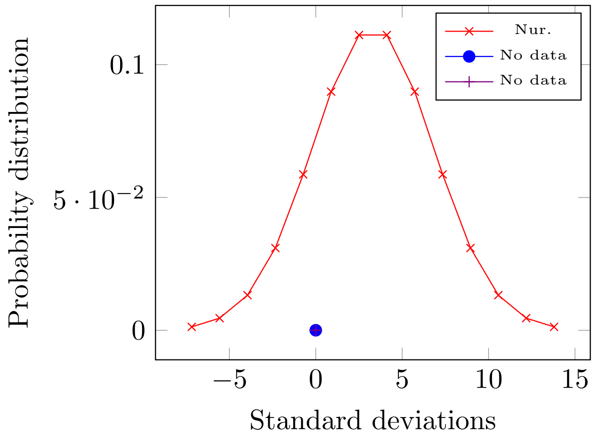
(a) Category 9



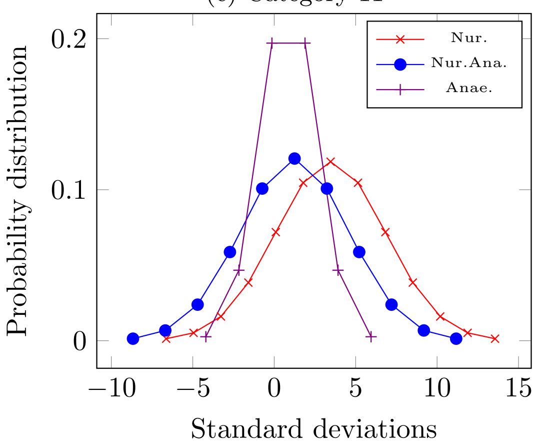
(b) Category 10



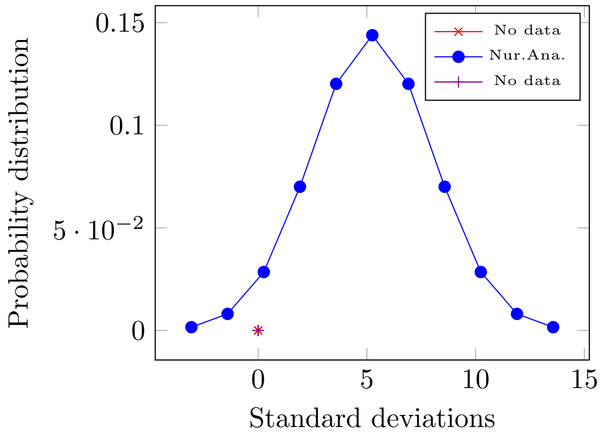
(c) Category 11



(d) Category 12



(e) Category 21



(f) Category 22

Figure 5.43: 3rd set of plots of normal distribution function for nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling

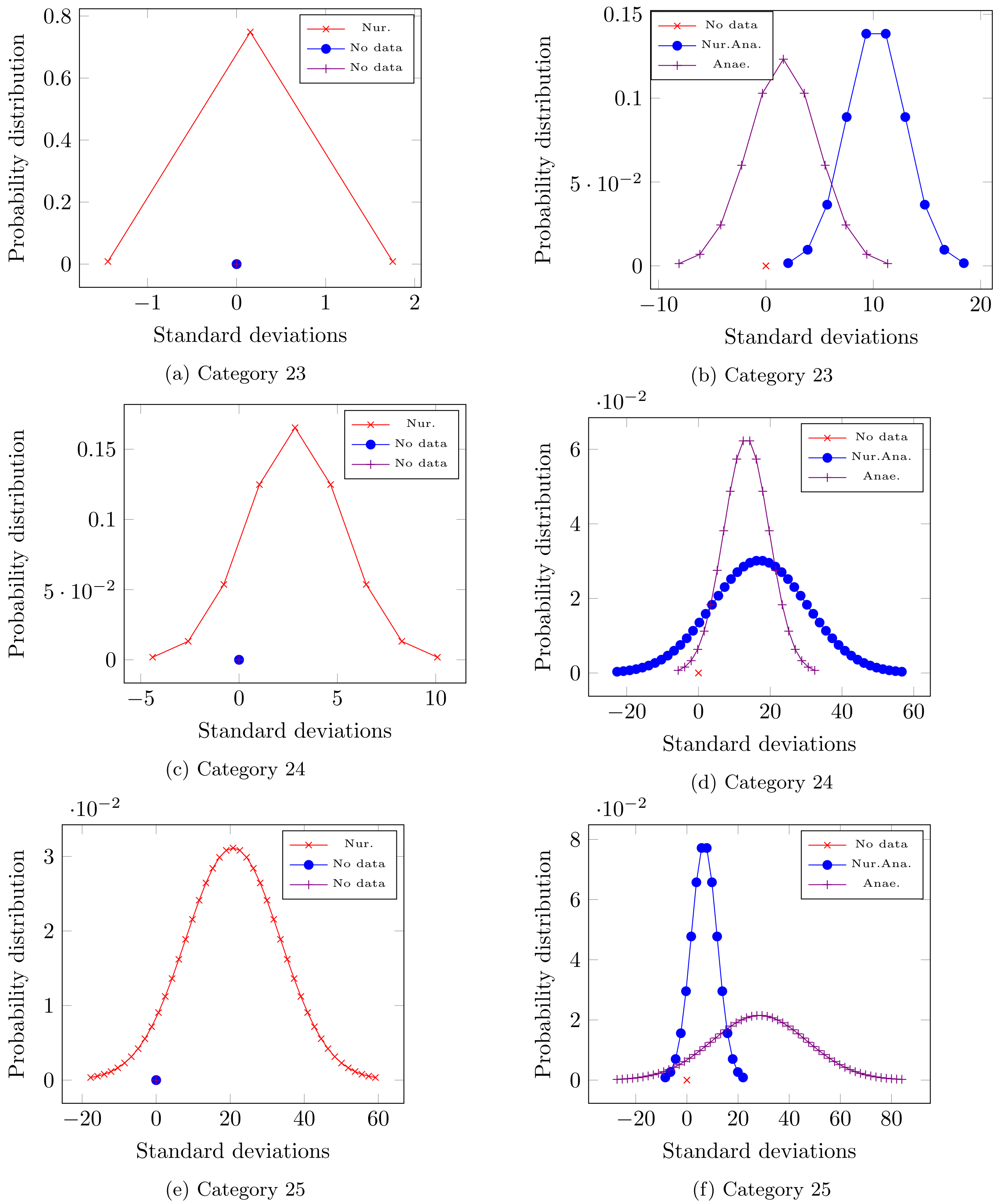


Figure 5.44: 4th set of plots of normal distribution function for nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling

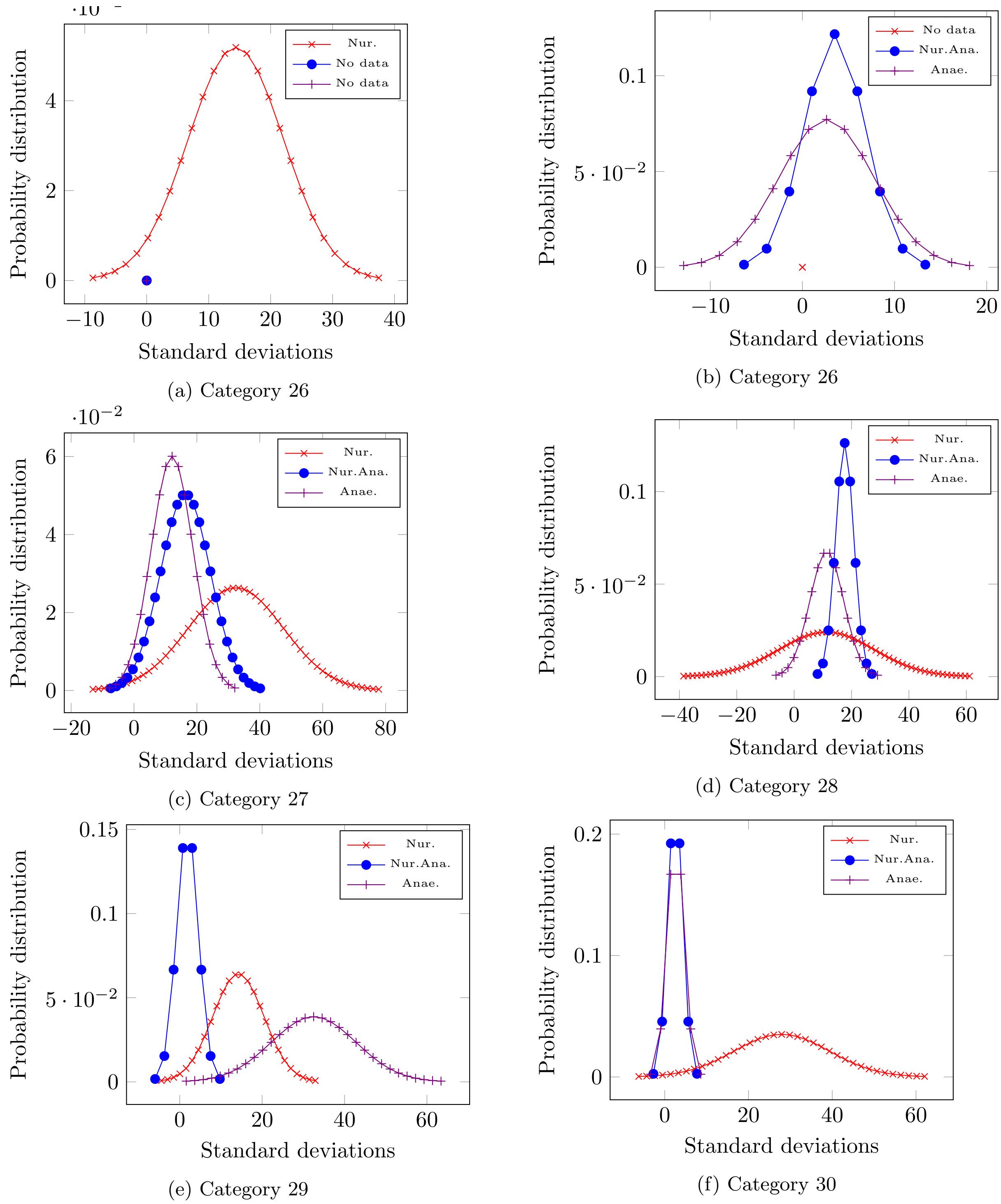
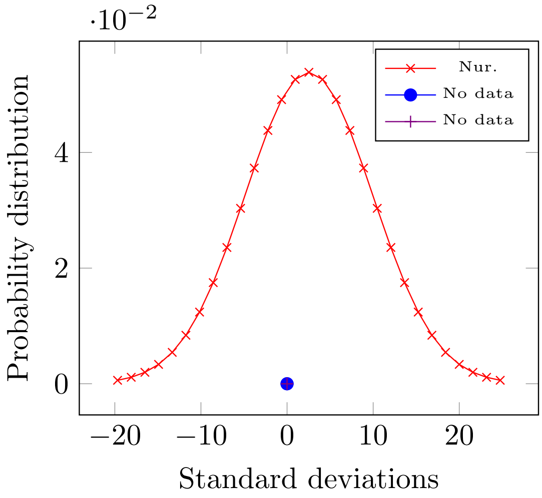
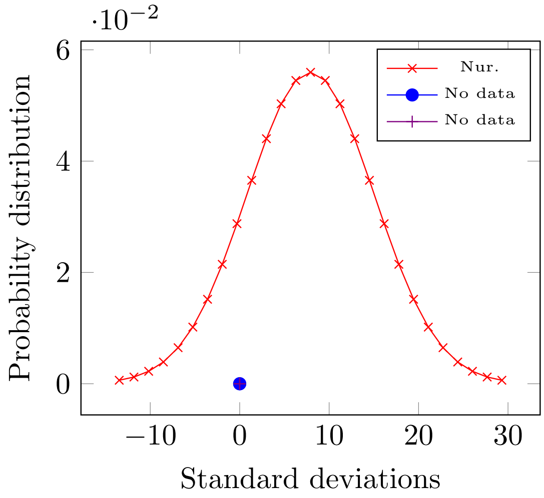


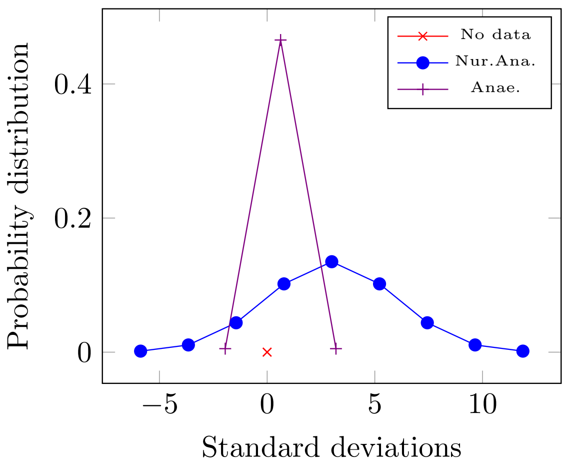
Figure 5.45: 5th set of plots of normal distribution function for nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling



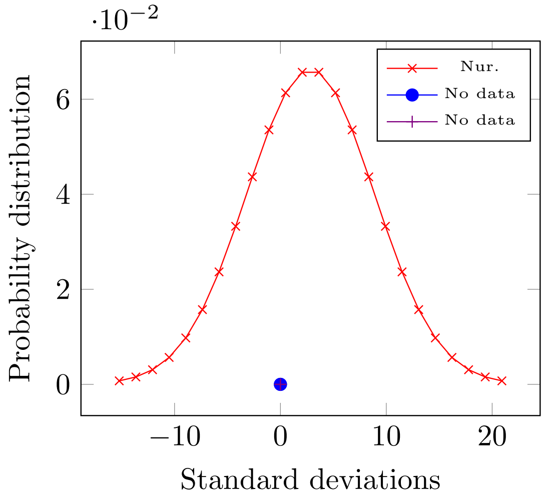
(a) Category 31



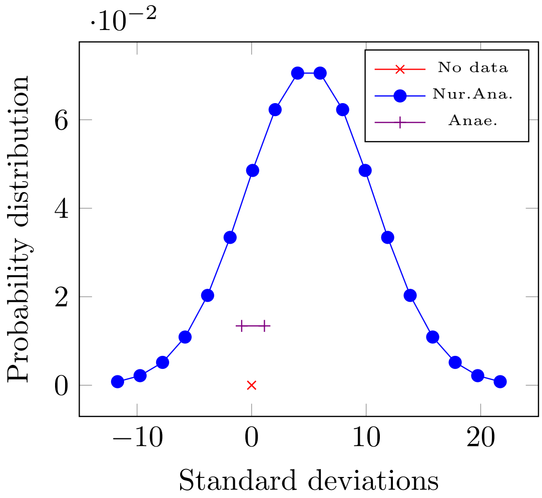
(b) Category 41



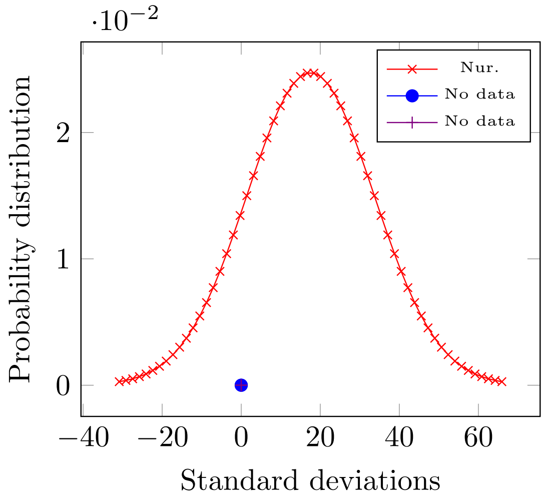
(c) Category 41



(d) Category 42

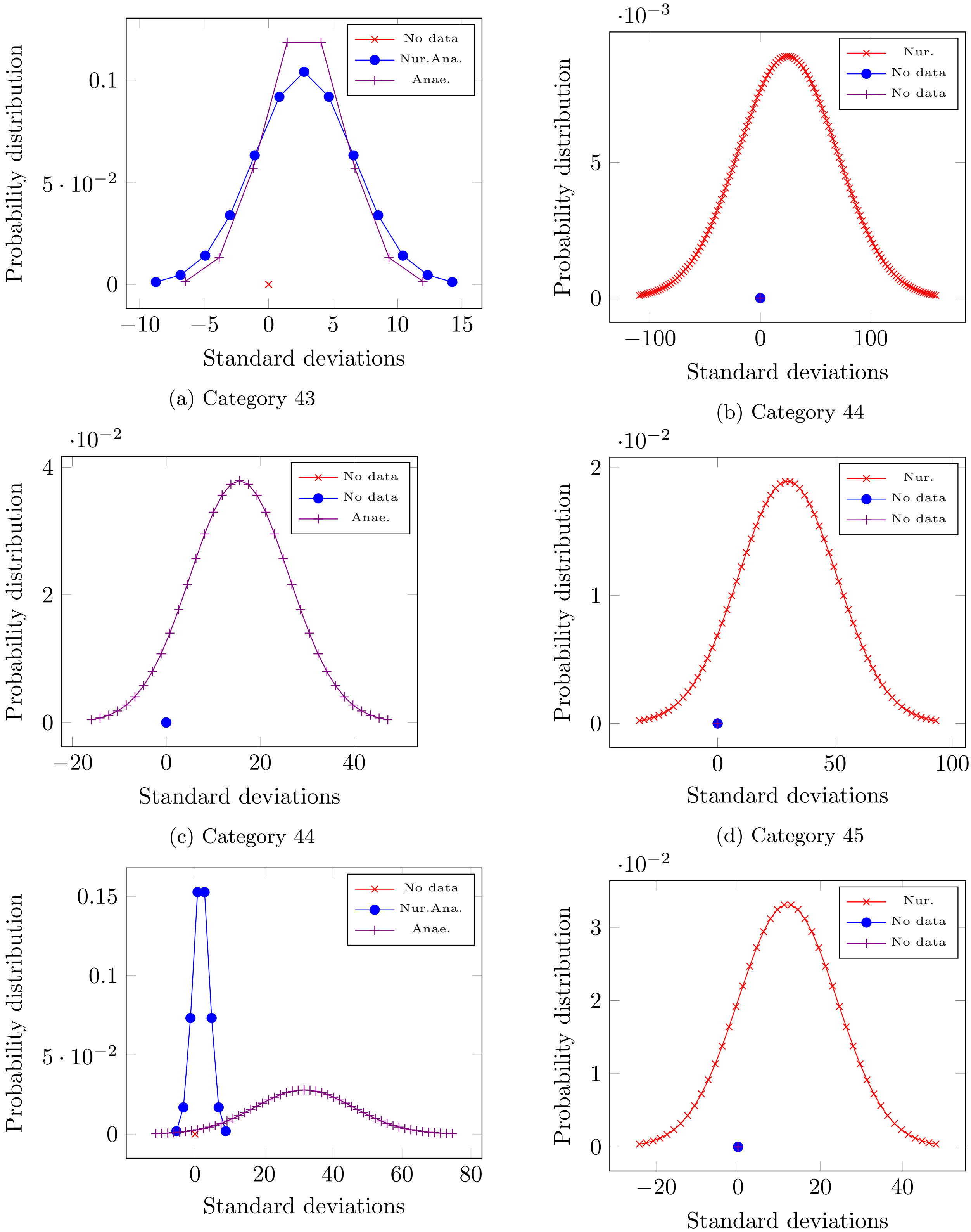


(e) Category 42



(f) Category 43

Figure 5.46: 6th set of plots of normal distribution function for nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling



(a) Category 43

(b) Category 44

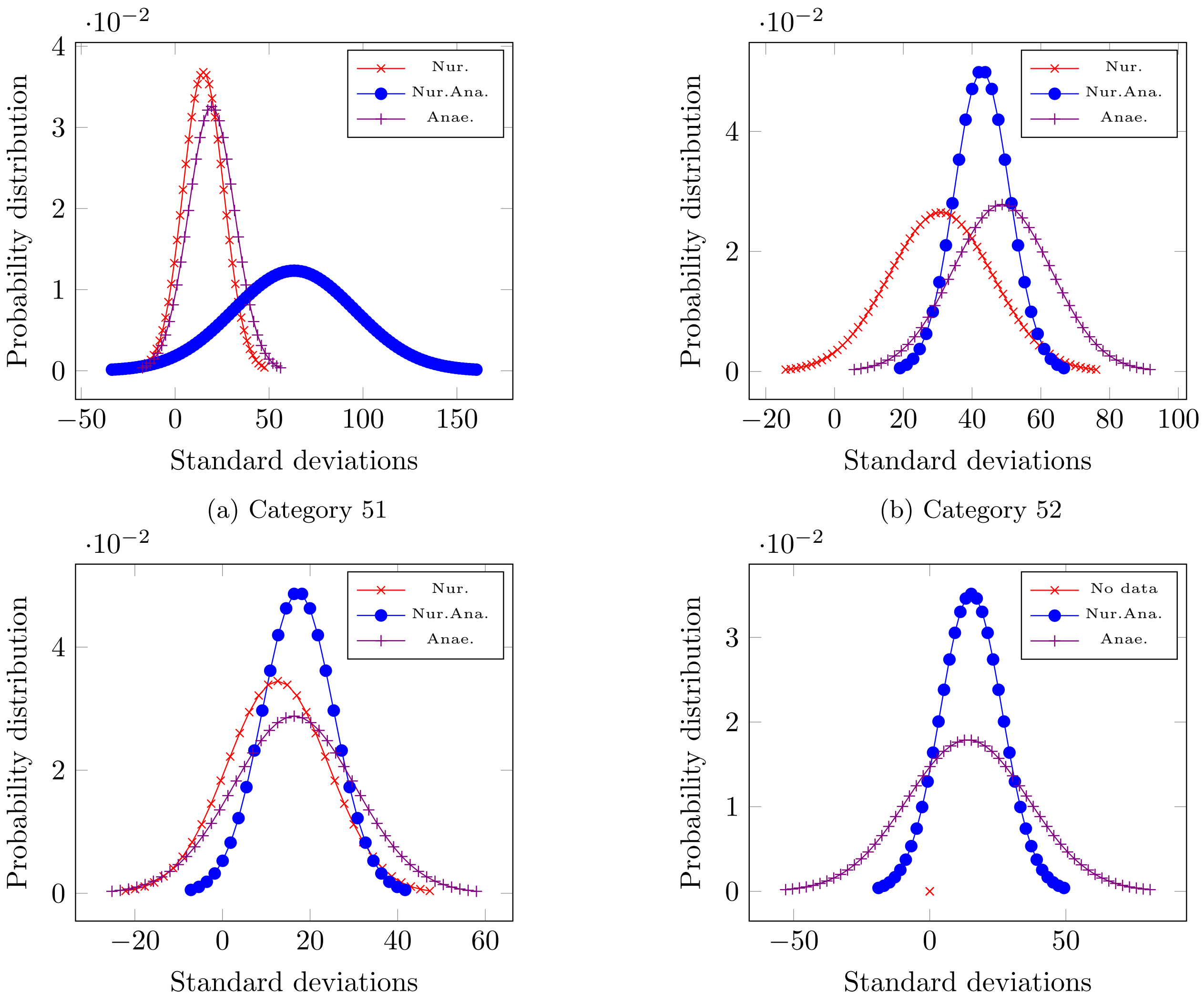
(c) Category 44

(d) Category 45

(e) Category 45

(f) Category 46

Figure 5.47: 7th set of plots of normal distribution function for nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling



(a) Category 51
(b) Category 52
(c) Category 53
(d) Category 54

Figure 5.48: 8th set of plots of normal distribution function for nurse, nurse anaesthetist, and anaesthesiologist schedulers based on data collected in the work sampling

CT.	Description	Nur.	Nur.Ana.	Anaesth.
1	Check-up on OR availability	78	7	17
2	Check-up with Nursing OR Board Runner/Unit Clerk	264	24	97
3	Check-up on Surgeons, Anaesthesiologists and Residents	39	8	133
4	Check-up on Nurse Anaesthetist availability	59	103	13
5	Check-up on material availability	99		
5	Add-on case staff scheduling		20	22
6	Cases moved from one OR to another	91		
6	Self checking patient at staging area		167	277
7	Add-on case staff scheduling	50		
7	Self working in OR		981	571
8	Stretcher stripping	4		
8	Patient (pain management) rounding		1	24
9	Self working / nursing help	84		
10	Staffing issue due to residents	14	0	
11	Opening (additional) OR room	3		
12	Staffing issue due to lunch / breaks	43	0	
21	Check for patient availability	45	10	7
22	On phone for blood request	0		
22	Writing on board breaks and lunch		42	0
23	On phone for supplies	2		
23	Writing on board for staff schedule		82	13
24	On pager to read message	37		
24	Discuss staffing with colleagues		136	107
25	Writing on board breaks and lunch	270		
25	Discuss (medical) issues with colleagues		54	227
26	Writing on board for staff schedule	187		
26	Check e-mail or Human Resource software		28	21
27	Discuss staffing with colleagues	421	131	97
28	Check e-mail or Human Resource software	147	141	91
29	Case tracking on OR display	185	15	260
30	Sending/receiving messages via pager, computer and phone	363	20	21
31	Late OR start reporting	33		

Table 5.7: Part (1): Categories (CT.) and a total number of random (registered) observations during the work sampling through job-shadowing the nursing staff scheduler (Nur.), nurse anaesthetist scheduler (Nur. Ana.), and anaesthesiologist scheduler(Anaesth.)

CT.	Description	Nur.	Nur.Ana.	Anaesth.
41	Helping with first OR start	103		
41	Helping to supply the material and pharmacy		24	5
42	Helping to supply the material	37		
42	Arrange equipment and material in OR		40	1
43	Arrange equipment and material	228		
43	Transporting patient		22	22
44	Rounding with nursing staff	321		
44	OR board runner and huddle meeting		0	125
45	OR board runner and huddle meeting	388		
45	Prepare weekly staffing schedule		14	253
46	Prepare weekly staffing schedule	157		
51	Relaxing (coffee, wash-room, small-talk)	195	507	155
52	Walking	402	343	390
53	Lunch break for self	164	138	131
54	Others (filled survey or discussion)		122	112

Table 5.8: Part (2): Categories (CT.) and a total number of random (registered) observations during the work sampling through job-shadowing the nursing staff scheduler (Nur.), nurse anaesthetist scheduler (Nur. Ana.), and anaesthesiologist scheduler(Anaesth.)

behind an unwanted activity, connect its origin in the business process, and implement appropriate measures for its minimization.

(b) As shown in figures (5.41), (5.42), (5.43), (5.44), (5.45), (5.46), (5.47) and (5.48), only a few categories (approximately 4 out of 33) exhibit normal distributions with the entire *bell curve*, a few (7 out of 33) show not-entire, and the rest (22 out of 33) show either partial or none.

(c) Owing to the lack of sufficient appearance of a few activities, these categories are represented using several *dots* only in the normal distribution plots. IoT devices such as wearable sensors, which recognise the type of activity being performed, may be used to collect the data. In such cases, large amounts of data, which can aid computer simulations or the training of machine learning algorithms, can be collected.

5.4.2 Advantage and limitation of the study

The insights gained from applying work-sampling in this study can be summarised as follows:

(a) The work sampling technique can be used to collect data in other hospitals and output histograms, pie charts, and normal distributions for further analyses.

(b) The results obtained from UMHS can be reused as they are based on random observation, creation of random inputs for simulation, and satisfaction of specific values for confidence and error[48].

While applying the work-sampling in this study, the following limitations were observed:

(a) The primary limitation of work sampling concerns the use of the gathered data; whether the performed activities' performance quality and why more or fewer activities consume more of the total workday in the OR-WPS process area cannot be inferred. The secondary limitations explain the activity relationship, correlation, and contemplation/thought behind it.

(b) As a shadow, the observer cannot usually enter the ORs. The classification of ongoing activities is based on the observer's interpretation and can vary accordingly.

(c) The observation can improve the performance of the observed people[49]. Therefore, a policy of minimum interference was adopted during the observation.

A simulation must help guide the management to decide on OR management when the resources are appropriately allocated, increase the productivity, and control the costs. Further, the data collected should aid real process improvement and contribute to a statistically sound representation of reality.

[48]Note: Special care must be taken while reusing the results as the data is in the healthcare domain.
[49]Source: Gustav Wickstroem (200), The “Hawthorne effect" - what did the original Hawthorne studies actually show? [WB00]

5.5 Survey Based International Comparison in OR-WPS

Sections (5.5.1) and (5.5.2) describe the detailed analysis and corresponding results.

5.5.1 Regression Analysis of Value Dimensions

On the basis of the published research on the case of BELOUGA for German hospitals wherein 172 physicians/surgeons and 246 nurses were surveyed using the questionnaire, a factor analysis was performed on the dataset. The particular questions (also known as *items*) were summarised using factor analysis and resulted in 8 factors (also known as value dimensions)[50]. The dataset was tested on KMO-value[51,52], which was over 0.9; the set was suitable for factor analysis. Although the significance of identified value dimensions was not part of the survey, it can be statistically estimated using *regression analysis*. The regression coefficients suggest the relative importance of the value dimensions within the overall satisfaction of the surveyed customers.

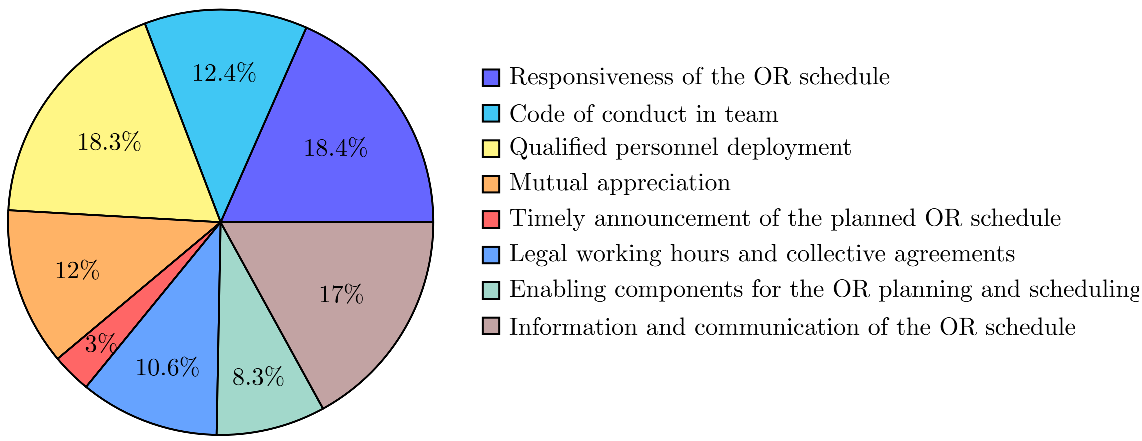


Figure 5.49: Relative significance of customer satisfaction value dimension indicators in the percentage of the total from a survey conducted in project BELOUGA

[50] In-depth source: Herbert Woratschek et al. (2015), Wertschöpfungsorientiertes Benchmarking [Wor+15b, pp. 229-236]

[51] Note: KMO measures the sample suitability according to Kaiser-Meyer-Olkin criteria.

[52] Source: Edward Cureton et al. (2013), Factor analysis [CD13]

As shown in figure (5.49), an updated value of the significance of the value dimensions as compared with the proceeding results is presented. The most critical value dimension of the OR-WPS was the *responsiveness of the OR schedule*, the possibility to accommodate the workforce's requests and changes regarding the OR schedule at 18.4%. The 2nd, 3rd and 4th most critical factors contributing to the overall satisfaction were the *qualified personnel deployment* at 18.3%, *information and communication* of the OR schedule at 17% and *code of conduct in a team* at 12.4%, respectively. Other dimensions are also shown in the figure with their importance.

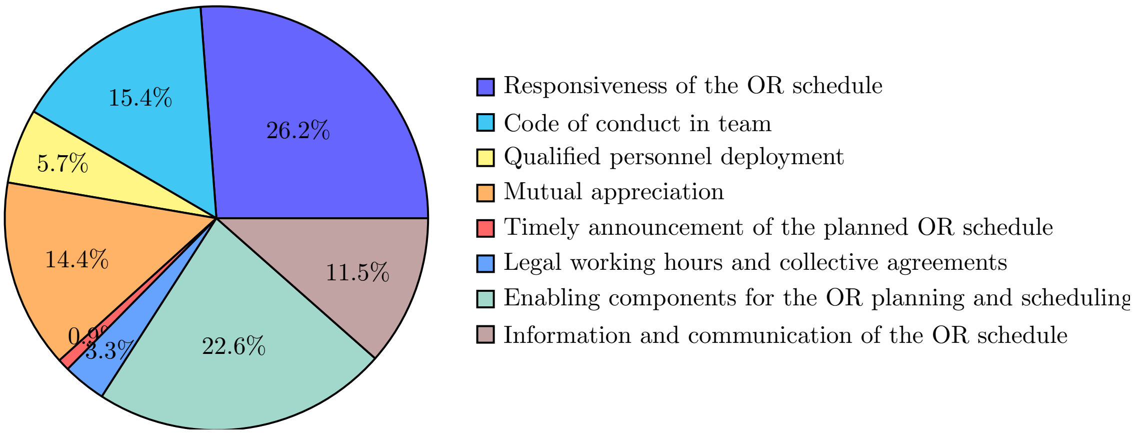


Figure 5.50: Relative significance of customer satisfaction value dimension indicators in the percentage of the total from a survey conducted at Missouri hospital or BELOUGA-M

Compared to the previously reported works, as aforementioned, this study entailed a survey conducted among the number of respondents at Missouri (USA), as shown in table (4.7), to examine the similarities and differences. The KMO value for total responses of both BELOUGA and BELOUGA-M (n = 501) was found to be 0.932; the dataset is suitable for factor analysis. Figure (5.50) indicates the relative significance of the value dimensions specific to Missouri hospitals. The most crucial value dimension of the OR-WPS at Missouri was the responsiveness of the OR schedule at 26.2% compared to German counterparts at 18.4%. The 2nd, 3rd, and 4th most important factors contributing to the overall satisfaction were found to be the *enabling components for the OR planning and scheduling* at 22.6% compared to 8.3% with the German counterparts, *code of conduct in a team* at 15.4% vs 12.4% in the German case, followed by *mutual appreciation* at 14.4% vs 12% in the German case, respectively.

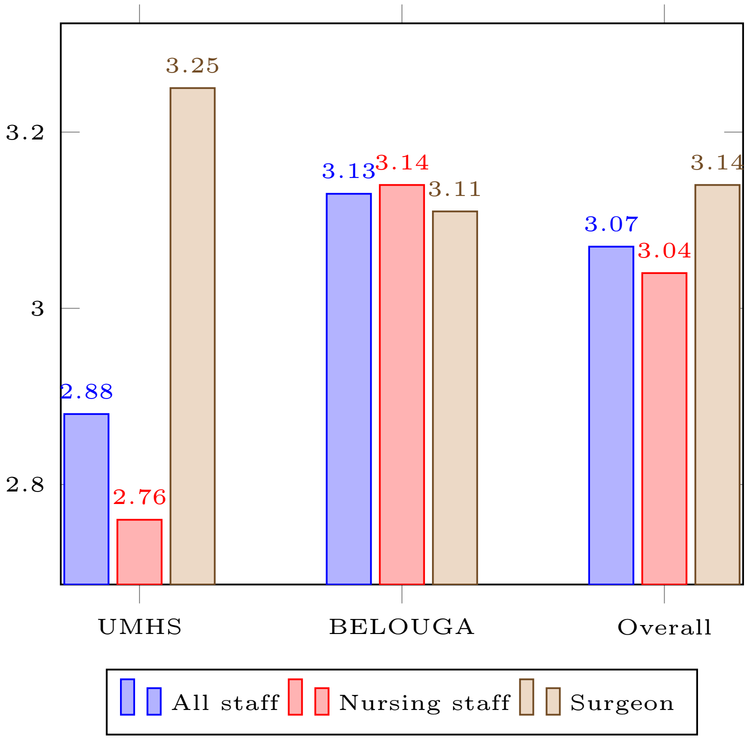


Figure 5.51: Comparison of overall (average) satisfaction among all roles in BELOUGA-M/UMHS n={110, 82, 28}; in BELOUGA n={337, 220, 157}; and overall n={447, 302, 185} respondents part in the surveys. Scale: 1=fully-satisfied, 2=very-satisfied, 3=satisfied , 4=less-satisfied, 5=unsatisfied

Further investigation comparing the values obtained from Missouri (in the context of benchmarking with BELOUGA outcomes) can be performed. As shown in figure (5.51), a comparison adds value to already validated and presented *value dimensions* and their *significance*. Figure (5.50) shows the overall satisfaction of the roles within OR-WPS. The stated values are based on the number of survey responses received (excluding those not received) out of the total questionnaires sent out to be completed. For example, in UMHS, 110 survey questionnaires were sent, 82 received, and 28 were invalid or not filled in. Based on the results in figure (5.51), the following conclusions can be drawn:

(a) There is no notable difference between UMHS/BELOUGA-M (at Missouri, USA) and BELOUGA (in German hospitals) (satisfaction values of 3.25 and 3.11, respectively) among surgeons (including anaesthesiologists). The overall value also does not differ significantly from those of UMHS and BELOUGA.

(b) The nursing workforce at UMHS is more satisfied (satisfaction value = 2.76) than their BELOUGA counterparts (satisfaction value = 3.14).

(c) The satisfaction within speciality groups overall (surgeons and nursing staff) is 2.88 for UMHS compared to 3.13 for BELOUGA.

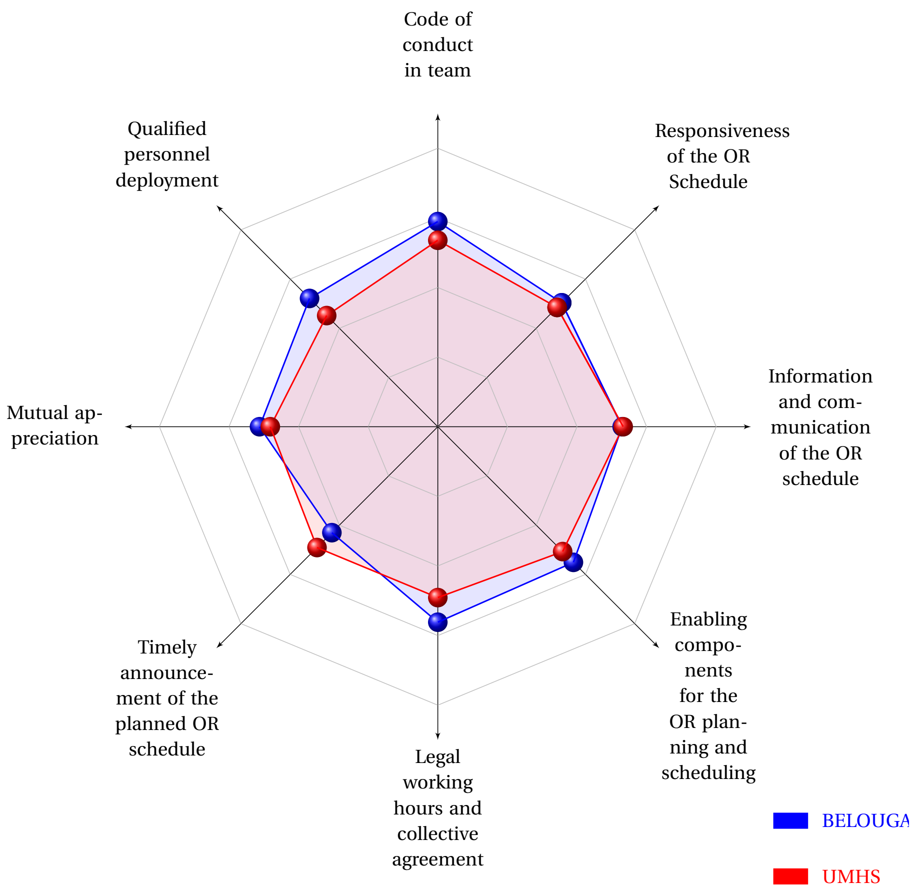


Figure 5.52: Overview of the characteristic mean values of the factors based on values in the table. Scale: 1 = very good (innermost circle), 2 = good, 3 = average, 4 = poor (outermost circle), 5 = very poor (not shown)

An in-depth analysis of the influences on overall satisfaction is provided by the overview of the characteristic mean values of the individual value dimensions as shown in table (5.9) between hospitals in UMHS/BELOUGA-M (a case of Missouri) and BELOUGA (combined value for few German hospitals) as shown in figure (5.52).

Category	*Values*	
	BELOUGA-M	**BELOUGA**
Responsiveness of the OR schedule	2.4238	2.5177
Code of conduct in team	2.6784	2.9471
Qualified personnel deployment	2.2580	2.6061
Mutual appreciation	2.4065	2.5616
Timely announcement of the planned OR schedule	2.4545	2.1525
Legal working hours and collective agreement	2.4545	2.8082
Enabling components for the OR planning and scheduling	2.5364	2.7554
Information and communication of the OR schedule	2.6633	2.6485

Table 5.9: Characteristic mean values of the factors plotted in the figure (5.52) in which 1 = very good, 2 = good, 3 = average , 4 = poor , 5 = very poor

In spider diagram (5.52), the nearer the values to the centre, the better are the value dimensions ranked by the survey respondents. A remarkable difference corresponds to the observation that the Missouri respondents have rated the dimension at *legal working hours and collective agreement* better than in BELOUGA counterparts. The differences between Missouri and BELOUGA are the greatest regarding the dimension—timely announcement of the planned OR schedule, legal working hours and collective agreements, qualified/skilled personnel deployment. For the hospital in Missouri to improve, it must maintain the values that are shown in the innermost regions and improve those which are noted in the outer regions.

As regards the relative significance or so-called weights of the value dimensions in BELOUGA's case, it was concluded that apart from two outliers, namely, the *timely announcement of the planned OR schedule* and *enabling components for the OR planning and scheduling*, all other value dimensions were located in the *top-right* or so-called *important* quadrant for overall satisfaction (see figure (5.53)). The exceptions, namely *legal working hours and collective agreement*, lie on the edge between less essential and essential quadrants for overall satisfaction[53]. Upon Comparing the results with that of UMHS/BELOUGA-M, the relative significance or weights of the same value dimensions are as shown in figure (5.54). The following interesting observations were made:

[53]Note: Detailed analysis and results are published by Woratschek et al.[54].

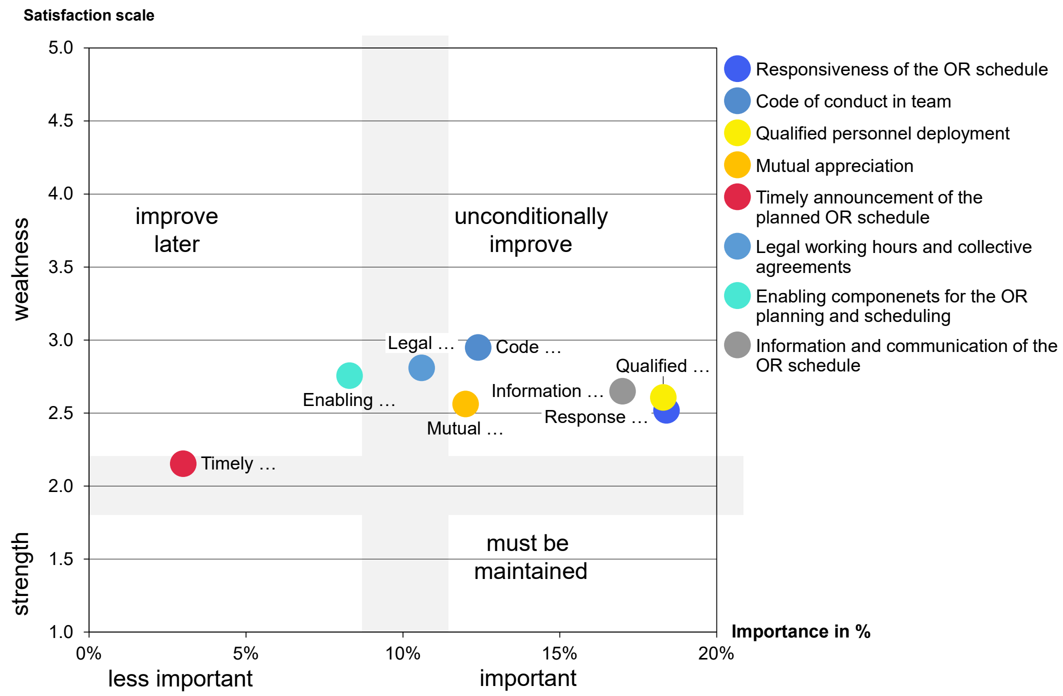


Figure 5.53: Overview of the strength and weakness in the form of a scatter chart for BELOUGA

(a) Certain value dimensions, namely, *qualified personnel deployment*, *timely announcement of the planned OR schedule* and *legal working hours and collective agreement*, lie in the *top-left* quadrant with *minor importance* label.

(b) The remaining value dimensions, namely *responsiveness of the OR schedule*, *code of conduct in the team*, *mutual appreciation and enabling components for the OR planning and scheduling*, lie in the *top-right* quadrant or with an *important* label.

The practical implication is that the *top-left* value dimensions can be *improved later*, whereas the *top-right* ones need improvement *unconditionally*. Only one value dimension, namely, *information and communication of the OR schedule*, lies on the edge between the *less important* and the *important*.

5.5.2 t–test Analysis

As described in previous section (4.4.2), a t-value can be used to determine whether to accept or reject a hypothesis. The calculation of the t-value for the difference

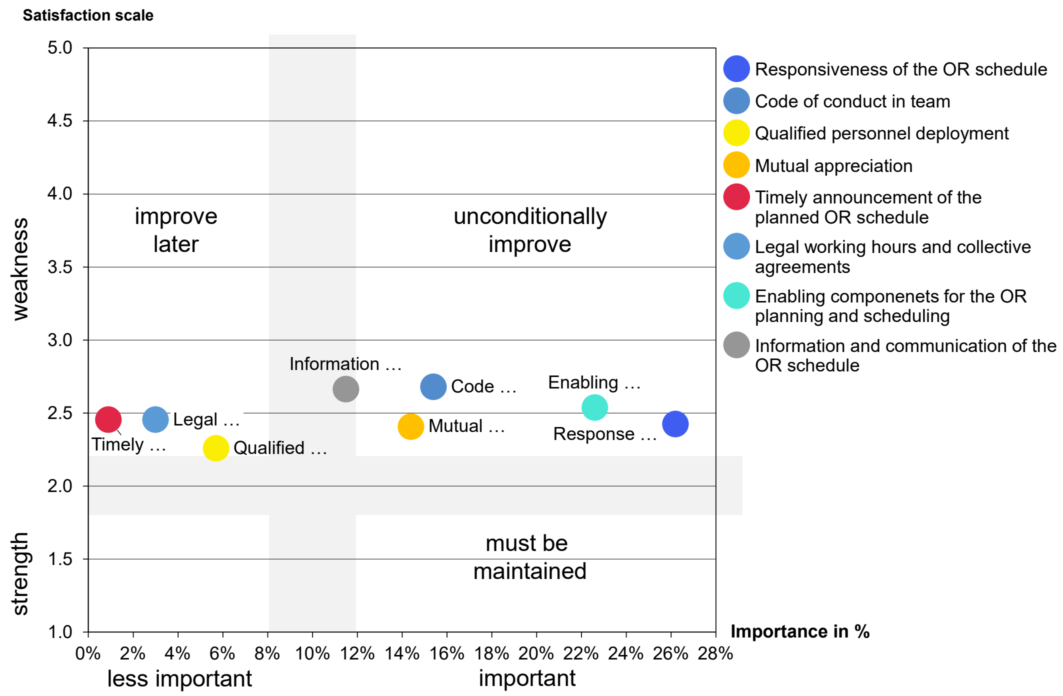


Figure 5.54: Overview of the strength and weakness in the form of a scatter chart for BELOUGA-M

between two βs is as expressed in equation (5.3).

$$t = \frac{b_1 - b_2}{\sqrt{s_{b_1}^2 + s_{b_2}^2}} \sim T(n_1 + n_2 - 4) \tag{5.3}$$

where:

b = Mean value (or estimator) of each sample
s = The standard deviation of the respective sample
n = Number of records in sample (1) and (2)
T = Degrees of freedom

As regards the overall satisfaction with the OR-WPS, there are remarkable differences concerning the importance of the two value dimensions, namely, *information and communication of the OR plan* and *enabling components for the OR planning and scheduling* (both having values of approximately 0.03), as shown in table (5.10).

	β-value BELOUGA-M	β-value BELOUGA	Sign.
Responsiveness of the OR schedule	0.440	0.391	0.553
Code of conduct in team	0.259	0.265	0.939
Mutual appreciation	0.241	0.256	0.831
Qualified personnel deployment	0.096	0.390	0.001
Legal working hours and collective agreements	0.056	0.225	0.031
Timely announcement of the planned OR schedule	-0.014	0.064	0.238
Enabling components for the OR planning and scheduling	0.379	0.177	0.001
Information and communication of the OR schedule	0.193	0.362	0.030

Table 5.10: t-value for the difference between two βs

Overlapping Confidence Intervals

(a) With regard to testing β-values for significance, Cumming et al.[55] have shown that two β-values are significantly different from each other if the 95% confidence intervals considered do not overlap more than 50%.

(b) Confidence intervals can overlap and indicate statistical significance

- At 50% overlap $\Longrightarrow$ sig. $p < 0.05$
- At 0% overlap $\Longrightarrow$ sig. $p < 0.001$

A concrete example in this regard is illustrated by the β-values from the value dimension called *code of conduct in team* and *information and communication of the OR schedule* in figures (5.55) and (5.56), respectively. In the case of the *code of conduct in a team*, the calculations for determining significantly different were performed, and they showed *no significant difference*[56]. In the case of *information and communication of OR schedule*, the calculation for determination of significantly different

[55]Source: Geoff Cumming et al. (2009), Confidence intervals [CF09]

[56]Note: Calculation for 95% confidence interval: In case of BELOUGA: 0.265 - 0.202 = 0.063; in case of UMHS: 0.414 - 0.259 = 0.155; Average = 0.109, which is further divided by 2 to get 0.0545 ≈

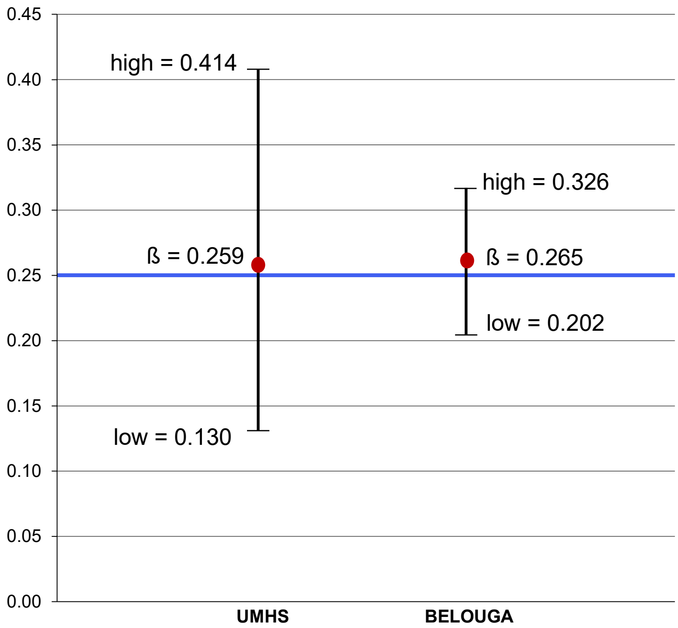


Figure 5.55: Comparison of overlapping confidence intervals with β-values case of UMHS/BELOUGA-M and BELOUGA concerning code of conduct in a team

or not was performed and showed *a significant difference*[57]. The aforedescribed results confirm that the t-test based on Cumming's method of overlapping confidence intervals for all concerned value dimensions was valid.

5.5.3 Conclusion of the study

Overall, the most critical lessons from the survey results are as follows:

(a) The value dimension information and communication of the OR schedule significantly *influence* the overall satisfaction with the OR-WPS in the surveyed German hospitals as compared to the UMHS.

(b) The value dimension enabling components for the OR planning/scheduling has a significantly *greater influence* on the overall customer satisfaction with the

0.055; Lower value (BELOUGA) plus divided average (0.202 + 0.055) = 0.257; the resulting small upper value UMHS 0.414 - 0.257 = 0.157 ($p > 0.05$), implying no significant difference

[57] Note: Calculation for 95% confidence interval: In case of BELOUGA, 0.265 - 0.202 = 0.063. In case of UMHS, 0.414 - 0.259 = 0.155. Average = 0.109, which is further divided by 2 = 0.0545 ≈ 0.055. Lower value (BELOUGA) plus divided average (0.202 + 0.055) = 0.257. Small upper value UMHS 0.414 - 0.257 = 0.157 ($p > 0.05$), implying no significant difference.

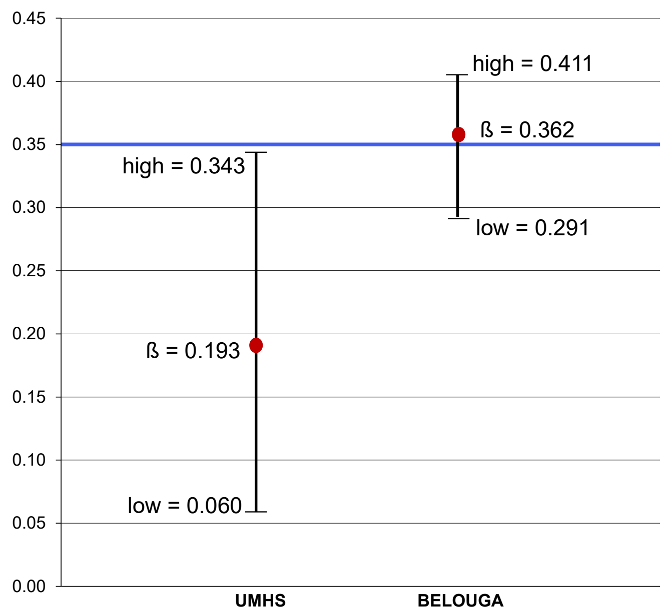


Figure 5.56: Comparison of overlapping confidence intervals with β values case of UMHS/BELOUGA-M and BELOUGA concerning information and communication of OR schedule

UMHS than at the surveyed German hospitals.

(c) The other value dimensions considered in this study, namely, *responsiveness of the OR schedule*, *code of conduct in a team*, and *mutual appreciation*, do not show significant differences.

(d) In contrast to the surveyed German hospitals, the value dimensions such as qualified personnel deployment, a *timely announcement of the planned OR schedule*, and *legal working hours, and collective agreements* do not significantly influence the overall satisfaction of the OR-WPS at the UMHS.

(e) The assessment of overall satisfaction with the OR-WPS also indicates that the OR medical workforce at the Missouri hospital is more satisfied with the OR-WPS than the German hospitals surveyed in the BELOUGA project.

The conducted surveys and their results afford a snapshot of the state of customer satisfaction. They can provide inputs for any improvements in the customer satisfaction of the OR-WPS process, as well concerning the related personnel or technology aspects. Real-world Changes must be guided by well-understood goals, and the findings, such as those from this study, can be combined with other reported findings such as those by Langley et al.[58].

5.5.4 Advantage and limitation of the study

The primary advantages in applying survey-based international comparison on OR-WPS are as follows:

(a) The questionnaire is an inexpensive method that can cover an increasing number of respondents from diverse healthcare systems.

(b) Scalability can be achieved using the same questionnaire with minor adjustments and more comprehensive respondents in many more areas leading to a good comparison.

During the survey and analysis of the results in this study, the following limitations were noted:

(a) Accessibility to the healthcare system of the respondents is not immediately granted and must pass the approval procedure of the regulatory board. The validity of questions in different healthcare business cultures must be assured, and the purpose of the questionnaire must be adequately understood.

(b) Respondents should answer the questions honestly; hence, there is always an inherent error associated with surveys. For instance, the questionnaire could not be entirely customised to the situation in the UMHS; this could lead to wrong answers.

5.6 Qualitative Study in OR-WPS Process Area

Sections (5.6.1) and (5.6.2) describe the results of this study and comparison with the survey, respectively.

[58] Source: Gerald Langley et al. (2009), The improvement guide - A practical approach to enhancing organizational performance [Lan+09]

5.6.1 Analysis and Comparison of Value Dimensions

The content analysis was performed using MAXQDA software, and the results are as shown in figures (5.57) and (5.58). On the basis of analysis, the essential value dimension of the OR-WPS at the UMHS was found to be qualified personnel deployment at 30.72%. The 2nd, 3rd, and 4th most essential factors contributing to the overall satisfaction were found to be as follows:

(a) The *mutual appreciation* at 26.5%

(b) *Responsiveness of the OR schedule* at 24.1%

(c) *Information and communication of the OR schedule* were at 7.23%, respectively.

The transcripts showed that nurses gain more flexibility, reputation, and annual salary if they qualify as nurse anaesthetists through continual education.

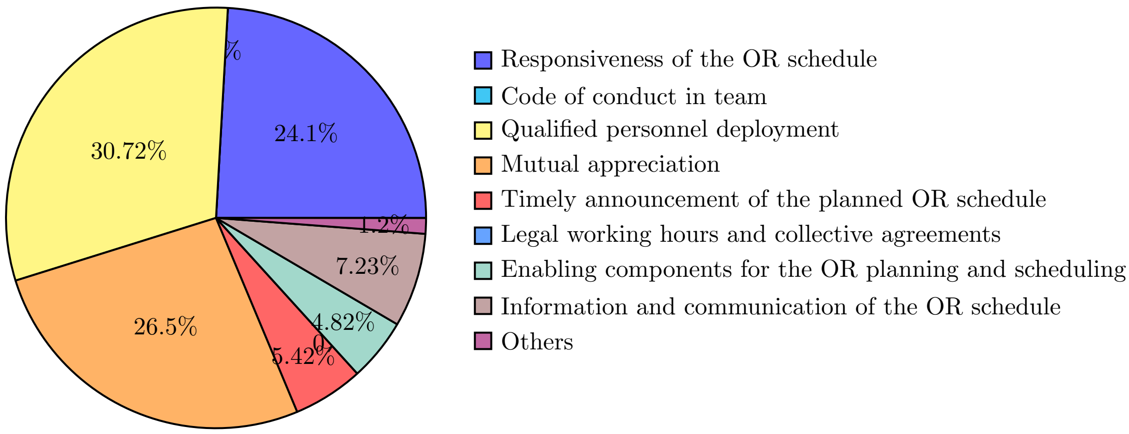


Figure 5.57: The relative importance of customer satisfaction value dimension indicators in the percentage of the total from a *qualitative data analysis* conducted at Missouri hospital

The pie chart in figure (5.57) describes the percentage values. In contrast, the stacked bar chart in figure (5.58) illustrates the absolute number of instances when the categories of the value dimensions were mentioned during the interviews and job-shadowing. It shows that the nursing workforce mentioned *mutual appreciation* the most (25 times), whereas the nurse anaesthetist mentioned the phrase 11 times; however, this is the 2nd most crucial value dimension in their case. Additionally, anaesthesiologists mentioned it 8 times, and for them, it is the 3rd most important. This observation leads to the inference that the nursing staff, in general, can have relatively more minor influence on the OR plan/schedule; however, they follow/are recipients of the OR schedule. This renders them less flexible; therefore, they seek *mutual appreciation* from other workforce groups and surgeons. Nurse anaesthetists and anaesthesiologists mentioned *qualified personnel deployment* as the most concerning 15 and 18 times, respectively. Observation of the surgeons/physicians was not part of content analysis; therefore, no conclusion could be reached about their preferences within the value dimensions.

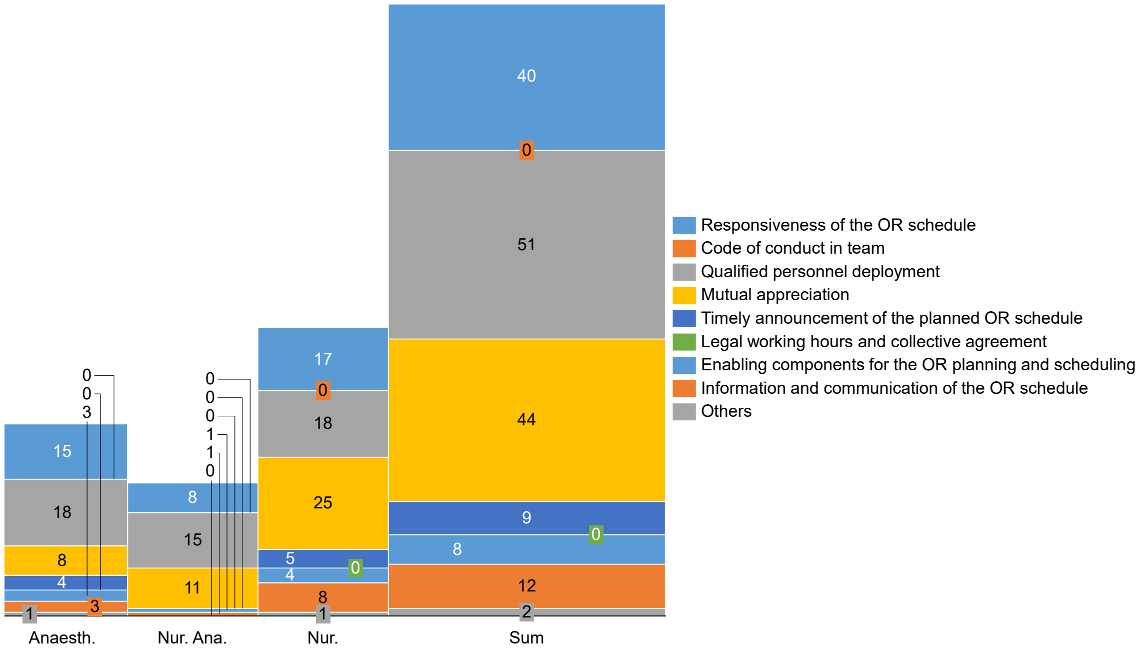


Figure 5.58: The relative importance of customer satisfaction value dimension indicators in absolute numbers from a *qualitative data analysis* conducted at Missouri hospital

5.6.2 Comparison with Survey

Although the two methods differ, the results from the survey, as presented in section (5.5), can be generalised. However, the content analysis results cannot be generalised. In BELOUGA and BELOUGA-M projects, *the responsiveness of the OR schedule* was found to be the most significant; it had values of 18.4% and 26.2%, respectively. Upon comparing them with the results of a content analysis of limited scope at the USA, the same value dimension was found to be the 2nd most important at 24.1% but is in some agreement with the survey results in the hospital in the USA with just 2.1% points difference. In contrast with an agreement between the results as aforementioned, there is another extreme observation. The survey in the BELOUGA-M project revealed that the workforce appreciates the *enabling components for the OR planning and scheduling* (at 22.6%), which is the 2nd highest value. By contrast, it was 4.82% in the content analysis; this is a 17.78% points difference. The values for *information and communication of the OR schedule* for the survey and content-analysis are 11.5% and 7.23%, respectively. The comparison does not lead to a concrete conclusion if content analysis can be fully trusted and generalised. It has limited scope, location, and coverage and is performed for a specific period. Therefore, it cannot be generalised compared to results from the survey in section (5.5).

5.6.3 Conclusion of the study

The following conclusions can be drawn on basis of the results in the figures (5.57) and (5.58):

(a) The value dimensions of *mutual appreciation*, *qualified personnel deployment*, and *responsiveness of OR schedule* are predominant for most of the observed nurses, nurse anaesthetists, and anaesthesiologists.

(b) Overall, the value dimensions such as *qualified personnel deployment* are mentioned, quoted, or observed the most during the job-shadowing of OR-WPS in the UMHS, followed by mutual appreciation and responsiveness of the OR schedule.

(c) Overall, the value dimension *enabling components for the OR planning and scheduling* is mentioned, quoted, or observed the second-least at UMHS job-shadowing followed by other value dimensions.

5.6.4 Advantage and limitation of the study

The primary advantages in applying qualitative data analysis on OR-WPS are as follows:

(a) The data for qualitative analysis is obtainable via work sampling, leading to synergy. The concept of coding the category in the transcript is easy. This is owing to the already available questionnaire and knowledge of the subject matter.

(b) It provided a deeper understanding of the research topic as the observer and observed subjects are together while data are being collected.

Further, while applying the qualitative data analysis in this study, of the following limitations were observed:

(a) The most significant limitation is the limited *interpretation*, *false interpretation*, and *observation of only limited events*. Qualitative content analysis cannot be generalised as it is not based on a sampling method.

(b) Although obtaining analysis results in terms of percentage and absolute numbers is possible, it could not provide a statistically expected outcome because qualitative content analysis is based on opinions and judgements by design. The replicability and reproducibility of the results are also limited. Generalization would not be possible as a large number of cases would be needed for testing.

6 Advanced Work

Abstract: *As do other domains, healthcare faces several challenges with regard to achieving BITA. Hospitals are a part of the critical infrastructure, or so-called HROs, of a country, and there has been an evident interest in applying new technologies suited for the complex business process in a multi-vendor environment. However, their IT landscape has been struggling with legacy systems. This chapter presents the use of EA frameworks in digitalising OR-WPS on the basis of simulation models. This study can serve as a reference in managing any future digital transformation of the hospital IT landscape.*

6.1 Introduction

This chapter presents the concepts of EA employed in this study for the digitalisation of OR-WPS by using computer simulation models. A PoC, with applicability in both practice and research, was devised in this study. The utility of involving EA is that it facilitates suitable planning and alignment with different actors in hospitals if computer simulation models such as ServiceSim OR-WPS are used to form the foundation for further digitalisation developments associated with healthcare service providers. Essentially, the following sections present the artefacts that could enable effective communication, partnership, and mutual agreements in this study as well as in any future advanced efforts.

6.2 Applying Enterprise Architecture on OR-WPS

In Section (2.1.5), it was mentioned how valuable it is to apply the EA in practice. A set of RQs, as mentioned in Section (4.6), are addressed in this chapter. Previously, Ahsan et al.[1] reported on the application of the EA framework to provide a detailed view for hospital management (without focusing on a computer simulation) to realise improvements in the premises of a British healthcare service provider. In order to simplify the complex decision-making for a transformation in a medium-size Portuguese hospital, Rijo et al.[2] used EA to improve the medical appointment and patient customer-service processes via interviews, questionnaires, and process maps. They described a simulation of possible strategic options and evaluations based on KPIs.

Recently, a primer on patient-oriented digitalisation in hospitals by Mangiapane et al.[3] presented a *base-model*[4] inspired by the EA framework to simplify decision-making for the benefit of its patients and other stakeholders in the service provision. The model provides an integrated view of the management, patients, processes, business, and persistence layers and the translation of the model to the current and future IT landscape transformation of a typical hospital. The following sections (6.3), (6.4), (6.5) and (6.6) present the application of the IAF framework, as shown in figure (4.23), to address the RQs.

6.3 Contextual Level - Why

The *contextual level* sets the foundation to address the *why* question. By providing context, one establishes a stable foundation for future analyses. The context would also help understand the healthcare provider's mission, vision, drivers, scope, business objectives, and principles. It would aid in positioning a computer simulation in the healthcare domain for creating a decision support system for the OR coordi-

[1] Source: K. Ahsan et al. (2010), Healthcare modelling through enterprise architecture: A hospital case [ASK04]

[2] Source: R. Rijo et al. (2015), Developing an enterprise architecture proof of concept in a Portuguese hospital [RME15]

[3] Source: M. Mangiapane et al. (2020), Patientenorientierte Digitalisierung im Krankenhaus [MB20, p. 51]

[4] In German: Grundmodell

nator/scheduler and OR manager[5]. Scholarly literature by Greefhorst et al.[6] also support this approach and recommends finding answers or statements for the enterprise/IT principles, mission and plans, constraints, and technology trends. On the basis of the scope of this study, business vision (6.3.1), PESTLE and SWOT analyses (6.3.2) similar to one proposed by Karagiannis et al.[7], architecture vision (6.3.3), technology trend (6.3.4), drivers and constraints (6.3.5), and architecture principles (6.3.6) are presented in this chapter.

6.3.1 Business Vision

The context can span the business process, data, and IT layers of architecture. The hospitals usually publish their vision documents. Two statements from the two cases obtained via field work/job shadowing are relevant; the first statement is from a German hospital[8]:

> "Our commitment to quality is founded on your trust."

The second statement is from the American hospital.

> "Through discovery and innovation, University of Missouri Health Care will be the health system that people choose for exceptional service and exemplary health care."

These two vision statements showed what the surveyed hospitals would prefer to become. They mentioned keywords such as *quality*, *trust*, *innovation*, and *exceptional service*, which are significant. Critically reviews of the vision statements provide (right) input and motivation for an architecture vision section (6.3.3). For the *business vision*, it could be validated that the hospitals aim to progress from just *conformance to quality* to higher maturity levels. Gale et al.[9] proposed a staged model. A customer-oriented business moves from the bare minimum, *conformance*, to customer service

[5] Note: All these inputs were either publicly available or in the shared documents. The business strategy was not considered, as this information was not shared during this study.

[6] Source: Danny Greefhorst et al. (2011), Architecture principles - The cornerstones of EA [GP11, p. 62]

[7] Source: Dimitris Karagiannis et al. (2020), Benutzerzentrierte Unternehmensarchitekturen [KMH20, p. 79]

[8] Translated from German to English

[9] Source: Bradley T. Gale et al. (2010), Managing customer value: Creating quality and service that customers can see [GW10]

quality, and then to a level of *delivering* customer value, as shown in figure (6.1), with graphical adaptions. A few analyses were performed, as detailed in the following section (6.3.2), to create a 360° view of the developments of the healthcare services in general and OR-WPS in particular.

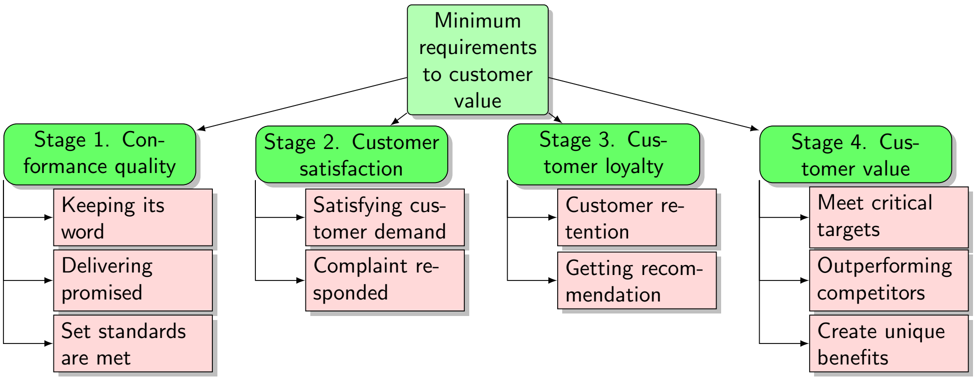


Figure 6.1: Business vision from conformance of quality up to the delivery of customer value in different stages

6.3.2 PESTLE and SWOT Analyses

This analysis sought to provide an outside-in followed by inside-out views. An *outside-in* view was created in the form of a political, economic, socio-cultural, technological, legal, and environmental (PESTLE) analysis of factors and their association with the outside (not necessarily technology) trends. The results are as shown in figure (6.2)[10]. Subsequently, an *inside-out* view was created in the form of an *associated* strength, weakness, opportunity and threat (SWOT) analysis. The SWOT elements are shown in figure (6.3)[11]. The elements in the SWOT analysis are based on the foundational work by Woratschek et al.[12]. Both PESTLE and SWOT add value by aiding in identifying the opportunities and mitigating the risks. The relationship among the PESTLE and SWOT elements is causal. Eventually, these analyses can be used to propose the PoCs or, in architectural terms, change initiatives. The architecture vision was framed as described in the following section (6.3.3).

[10]Note: An *assessment* is exhibited as *magnifying glass* and *driver* as *wheel*.
[11]Note: A *driver* is exhibited as *wheel*.
[12]Source: Herbert Woratschek et. al. (2015), Wertschöpfungsorientiertes Benchmarking [Wor+15b]

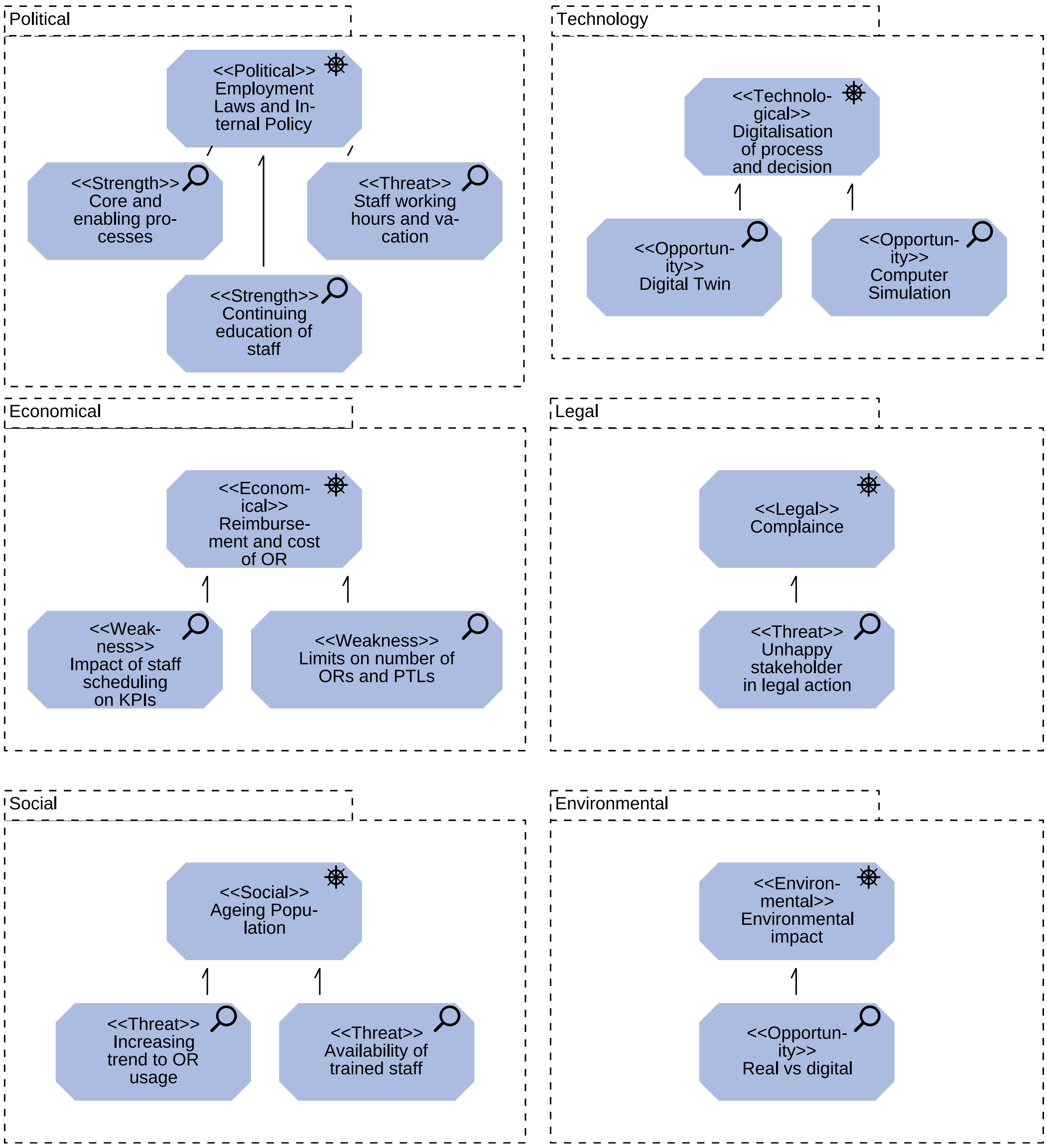


Figure 6.2: A catalogue of PESTLE and its relation to SWOT (6.3) in the context of (research) project modelled in ArchiMate® language

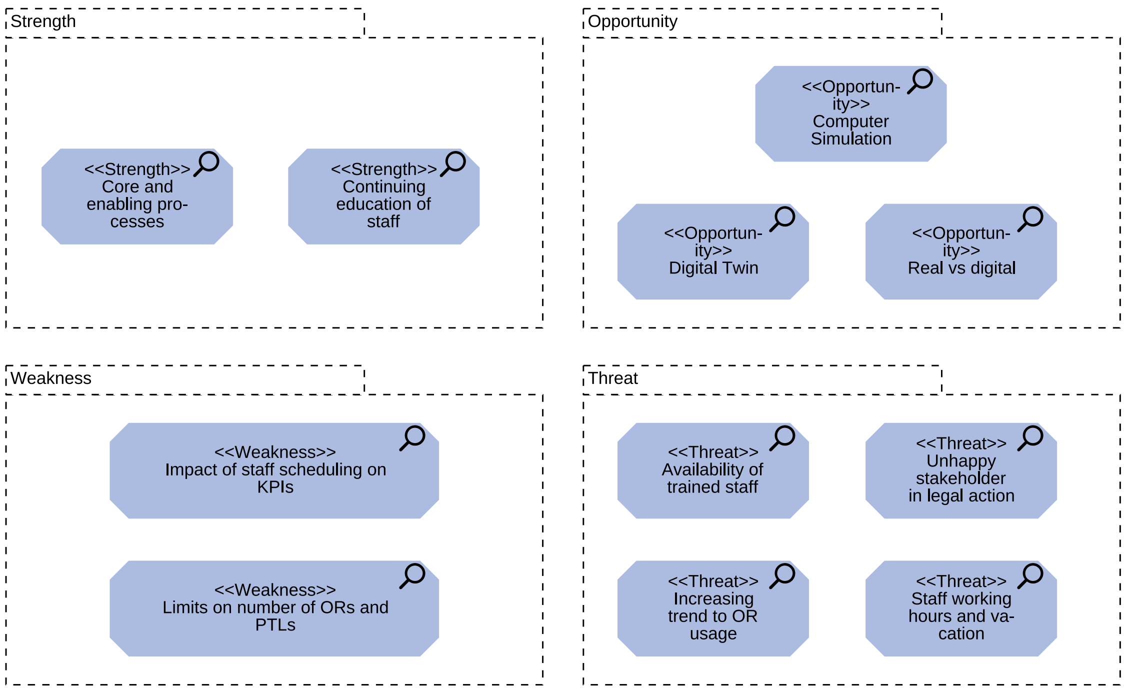


Figure 6.3: A catalogue of SWOT in the context of this work modelled in ArchiMate® language

6.3.3 Architecture Vision

A vision, as the term is used herein, defines a future *conceptual* state of the OR-WPS and a novel computer simulation (a DT) based DSS in the IT landscape. It can support the stakeholders of the OR-WPS in operational decision making, for example, optimising productivity, quality, cost, and customer satisfaction. A vision statement in this regard is as follows:

> "Conceptualize and implement a computer simulation capability, and prove its utility in the healthcare service business, which can ultimately support an organization to reach its strategic objectives and business goals."

This study investigated whether the new architecture vision (as stated above) can be addressed via a systematic architectural analysis. The following section (6.3.4) describes the technology trends which can be essential for the healthcare services domain in the future.

6.3.4 Technology Trend

As reported by Gartner[13], the top 10 strategic technology trends for the year 2020 were hyperautomation, multiexperience, democratization, human augmentation, transparency, and traceability, which were identified as people-centric[14]. As regards the healthcare service domain, according to Gartner[15], technology trends relevant to this study include DTs in healthcare, digital health platform, AI healthcare advisors, and automated patient decision aids. On the basis of these inputs, a set of technologies modelled in ArchiMate® language, as shown in figure (6.4), is considered interesting for future healthcare services.

One of the trends indicated that DTs, as mentioned in figure (6.4), are relevant in examining diverse phenomena in physical and engineering sciences as well as healthcare services. In the healthcare context, Croatti et al.[16] provided evidence of its usefulness in a medical trauma department. A DT model of OR-WPS can be *situationally aware* of supporting real-time decision making by using simulation models. The definition of situational awareness by Endsley[17] is as follows (6.24):

Definition 6.24. *Situational Awareness*

> *"Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." [End95, p. 36]*

A DT model was devised on the basis of these inputs, as shown in figure (6.5). It has the enabling process (EP) OR-WPS at the centre, whose activities are performed mainly by critical stakeholders such as OR coordinator/scheduler and OR manager. An OR scheduler assigns human resources to run the process. The internal customers of the OR coordinator/scheduler are the OR nurses. A patient is the final

[13] Source: `http://www.gartner.com/tech-trends`

[14] Note: Gartner had also identified empowered edge, distributed cloud, autonomous things, practical Blockchain, and AI security as leading trends. Hyperautomation can be realised via robotic process automation (RPA) and intelligent business process management suites. Hyperautomation would utilise AI tools, and machine learning (ML) is predicted to realise a fully automated operation.

[15] Source: `http://www.gartner.com/healthcare-trends`

[16] Source: Angelo Croatti et al. (2020), On the integration of agents and digital twins in healthcare [Cro+20]

[17] Source: Mica Endsley (1995), Toward a theory of situation awareness in dynamic systems [End95]

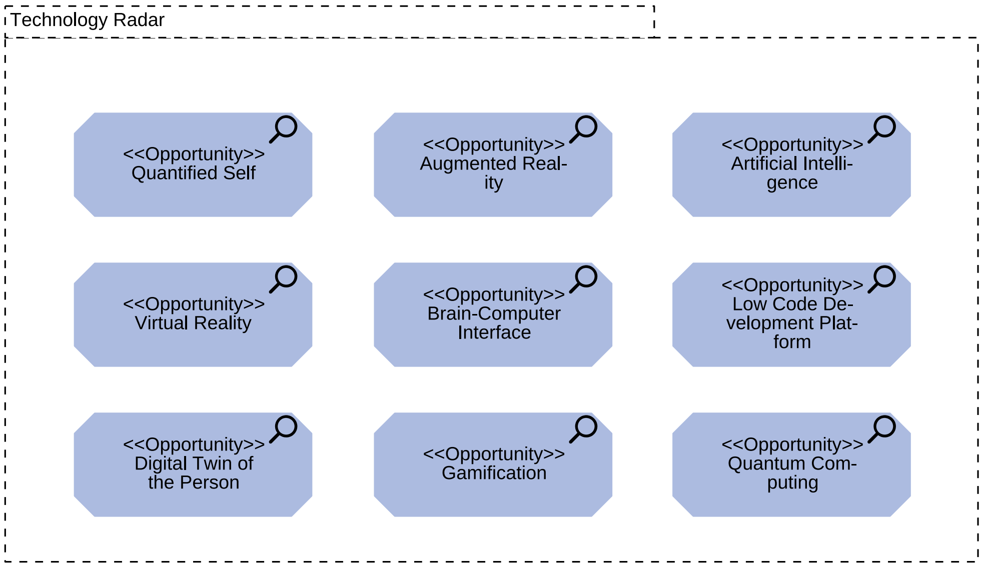


Figure 6.4: The technology radar specific to OR-WPS in ArchiMate® modelling language

customer and service receiver. Alternatively, the OR coordinator/scheduler and OR manager act *responsible* and *accountable* for the business process OR-WPS respectively. The OR-WPS is associated with a new *strategic capability* known as "OR-WPS DT simulation". It is then expected that the new capability could *measure* productivity, quality, cost, and workforce/customer satisfaction during a simulation experiment. These are the so-called *drivers* for further process improvement. Thus, the simulation can be considered situationally aware of its environment. The drivers and constraints of the DT from field study/job shadowing and previous research by Woratschek et al.[18] are modelled to further refine the digital twin concept. They are presented in the following section (6.3.5).

6.3.5 Drivers and Constraints

The scope of the architecture-based study was to systematically determine how a computer simulation can support reaching the efficiency and effectiveness goals of the hospital, explicitly using the supporting business process as a pilot. In figure (6.6), a model of the relationship among stakeholders, drivers, (resource) constraints and any assessment is presented. The stakeholders, such as department heads

[18]Source: Herbert Woratschek et al. (2015), Wertschöpfungsorientiertes Benchmarking [Wor+15b]

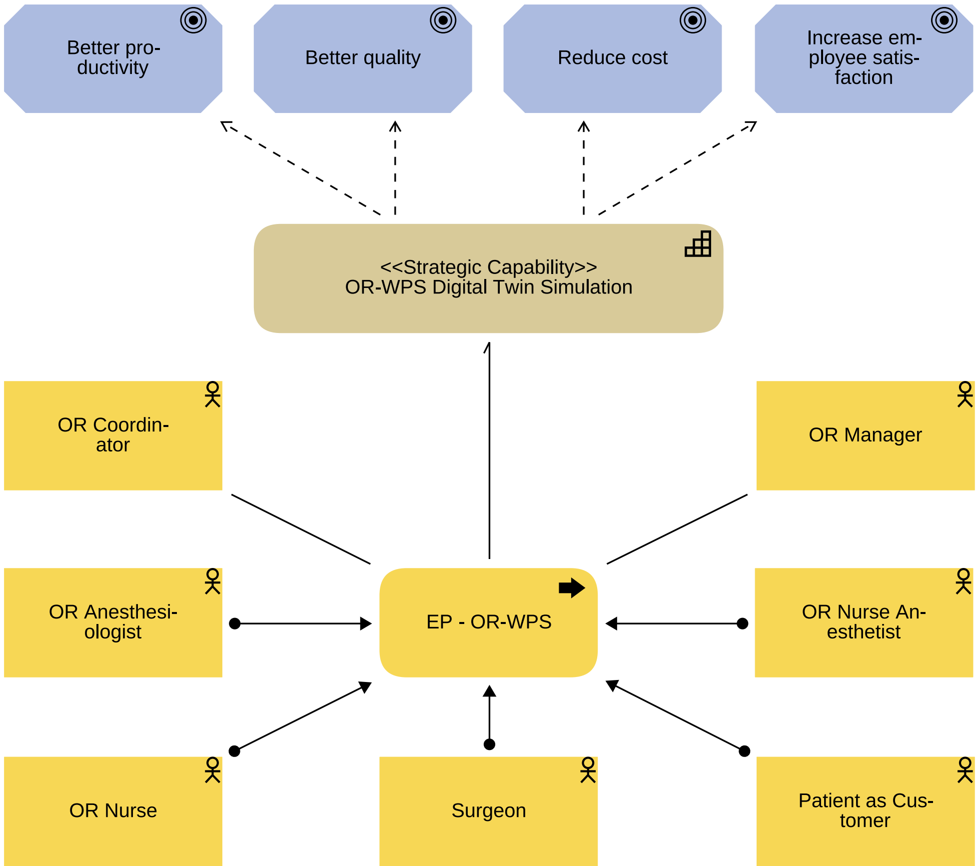


Figure 6.5: Proposed simulation-based DT business-capability of a hospital for OR-WPS DSS modelled in ArchiMate® language, which can be applied in a typical hospital

of various ORs, have a *business role*. The OR nurse provides a *healthcare (business) service*, and the healthy patient leaving the hospital is a *healthcare (business) goal*. A (higher) quality of service is a *driver*; the availability of skilled workforce is a *resource constraint*. Customer (workforce) satisfaction is a *value created*, and digitalisation of the business process pursued through simulations is an *assessment*. These models in ArchiMate® provide advantages such as maintainability and sustainability. They could help refine the ideas before the actual design and implementation of the simulation. Based on the vision, technology trends, drivers, and constraints, a few architecture principles were developed, as presented in the following section (6.3.6).

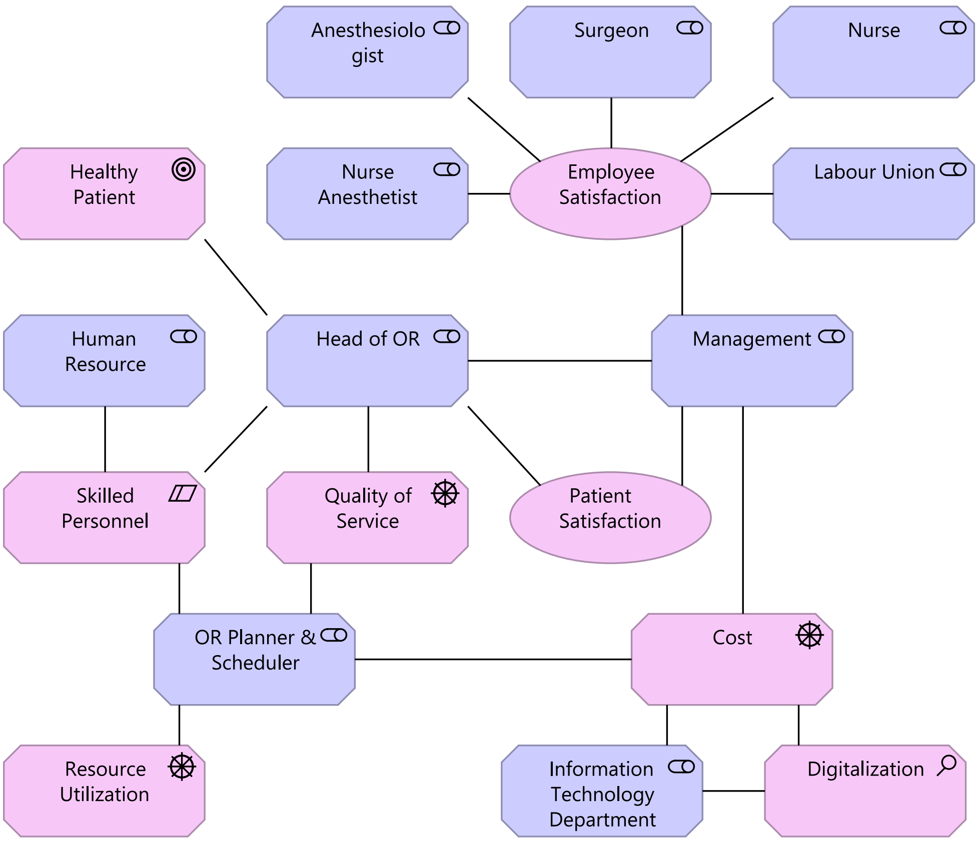


Figure 6.6: A model of surveyed hospital stakeholder concerns (driver, constraint, assessment) in ArchiMate®

6.3.6 Architecture Principles

In an organization with an architecture team, the *architecture principles*[19] would be conceptualised, discussed, validated, and presented to an *architecture board* or similar governance body. In this work, the architecture principles were collected based on the inputs/feedback from the surveyed hospitals. The term architecture principle[20] can be defined as follows (6.25):

Definition 6.25. *Architecture Principles*

> *"Architecture principles are a set of principles that relate to architecture work. They reflect a level of consensus across the enterprise, and embody the spirit and thinking of existing enterprise principles. Architecture principles govern the architecture process, affecting the development, maintenance, and use of the enterprise architecture."*

Figure (6.7) presents brief statements of the six architectural principles[21]. They guide the future steps, such as the *what* and *how* of any future PoC.

[19] Note: “Principles are general rules and guidelines, intended to be enduring and seldom amended, that inform and support the way in which an organization sets about fulfilling its mission” [Ope20]

[20] Source: https://pubs.opengroup.org/architecture/togaf91-doc/arch/chap23.html

[21] Note: All these principles must confirm with a statement, rationale, and implications; for simplicity, they are not elaborated further herein.

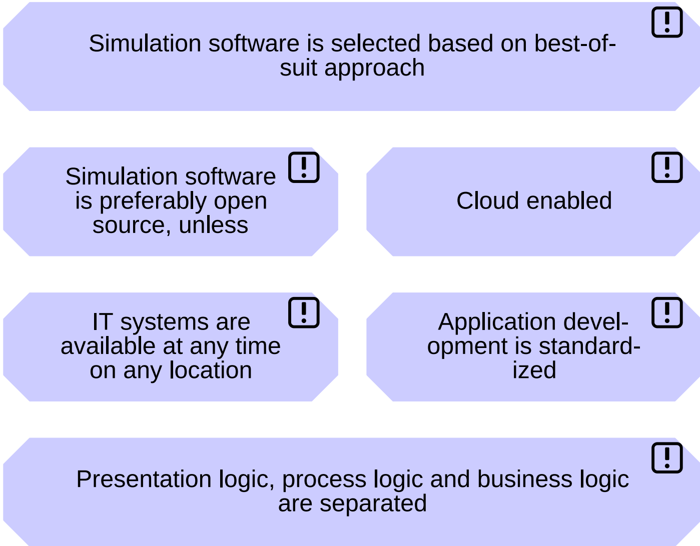


Figure 6.7: List of architecture-principles to be followed in this work modelled in ArchiMate® language

6.4 Conceptual Level - What

The *what* question is to be addressed at a *conceptual level*. This concerns the *business architecture*. The business architecture intends to model the operational organization of ORs from the perspective of OR-WPS, independent of the technology employed by the organization. The concept discussed herein is the healthcare provider's business architecture, which includes the business requirements (6.4.1) and business process[22] (4.2.2) under consideration, including the current state (as-is) of the process, physical architecture (6.4.2), and information systems architecture (6.4.3). By creating models and their views, gaps between the current process and future state comprising computer-simulation based DSS were identified in this study.

6.4.1 Business Requirements

Usually, the *business requirements* describe what the stakeholders would expect from a business system under consideration to deliver or perform. Therefore, getting the requirements right is essential at the conceptual modelling level. During the sur-

[22]Note: The concept of business process is introduced in a previous section (4.2.2), focusing on methodology, and further mentioned as part of the results in section (5.2).

vey of the hospitals, publicly available information was found from what the business of healthcare services aim to achieve as output from its processes. Four business principles, which set the business requirements (or expectations) from the business-processes are listed as follows:

(a) **We want satisfied patients**: "We consciously perceive our environment through the eyes of the patient, and we face his expectations every day. We put him in the centre of attention and respond to his wishes and worries. We combine all our professional skills with human warmth and respect to realise the patient's chances and respect limits."

(b) **We want to become constantly better**: "We place high and comprehensive demands on the quality of our services. In order to meet the quality requirements, we are constantly developing new ideas and improvements and implementing them. The feedback received are an opportunity to improve ourselves further."

(c) **Together we achieve our goals**: "We are committed to motivating and competent employees to identify with our company. Openness, personal esteem and mutual trust form us into an effective team. We maintain an open communication culture. Through extensive scope for decision-making, we enable each employee to solve his or her tasks independently, quickly and flexibly. Intensive training and further education are the foundation for this. We strive for successful and sustainable cooperation with our employees and external partners."

(d) **Profitability secures the future**: "We strive for economic efficiency with high quality. It requires performance and economical and ecologically sensible use of resources. In this way, we contribute to our company's long-term success and further development."

Because this study focused on OR-WPS, the translation of these business principles can be made in terms of business requirements as follows: not only the patients but also the workforce should be satisfied; the quality of process output should continually improve; workforce motivation should be maintained; and both productivity and cost must be optimised to achieve operational excellence.

6.4.2 Physical Architecture

ORs are one of the costliest assets operating in hospitals. A missing equipment or insufficient or unskilled workforce in the ORs can negatively influence the costs. The *physical infrastructure*[23] that the OR-WPS supports is as depicted in figure (6.8). Although the listed ORs in figure (6.8) are not mutually exclusive and collectively exhaustive, they are all *associated* with the ORs (healthcare) *capability* of the hospital. The ORs use IT applications to acquire the patient healthcare data and to operate the medical equipment. The ORs are the physical host to conduct any surgery type. They have an *associated* sterile material, medical equipment, and other material to fulfil their healthcare-service requirements. A high-level view of the distribution network is shown in figure (6.8) to ensure that the materials having the appropriate quality reach the right place at the right time, in appropriate quantities.

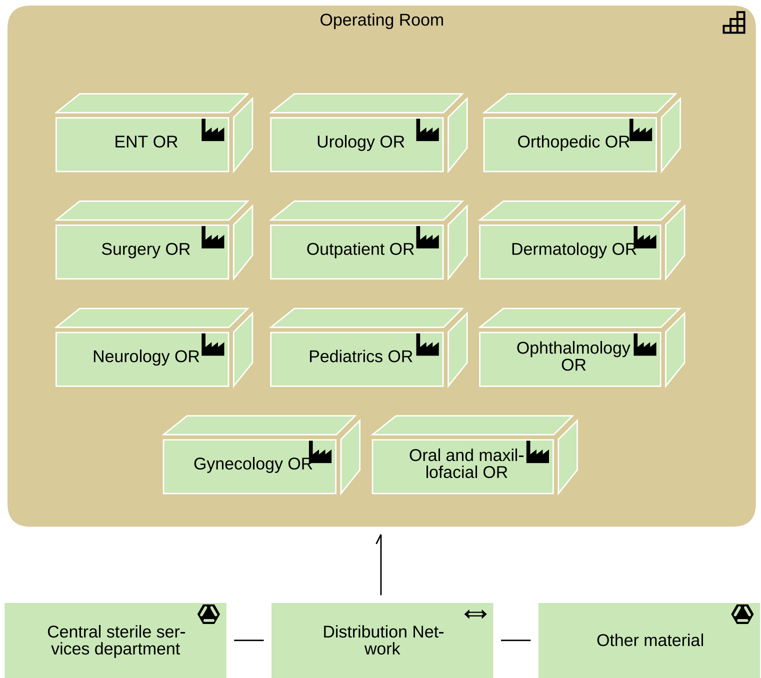


Figure 6.8: A view of the physical infrastructure architecture of types of the ORs in a hospital with service delivered by the sterile department and other supplies via a distribution network modelled in ArchiMate® language

[23]Note: As aforementioned, this study scoped OR-WPS; however, the physical infrastructure architecture is considered here to understand the big picture.

Another view of the physical architecture is from the service perspective, as shown in figure (6.9). Alternatively, service groups, such as nursing and anaesthesiology, collaborate but are dependent on cleaning, sterilisation, and supply stakeholders, who are ultimately dependent on the physical infrastructure such as equipment and availability of ORs. Alternatively, service groups realise the OR-WPS via OR schedulers/coordinators. The surgeons also function in collaboration with service groups to execute medical operations. Macario[24] identified several factors contributing to OR inefficiency. These factors are excess staffing due to inefficient OR allocation, start-time tardiness, case cancellation rate on the day of surgery, post-anaesthesia care admission delays, contribution margin (mean) per hour, turnover time, and prediction bias. Other studies focus on the ORs efficiency aspect, thereby validating that ORs are still an important topic in healthcare. Physical infrastructure is supported by an information system to automate repetitive tasks; this is the focus of the following section (6.4.3).

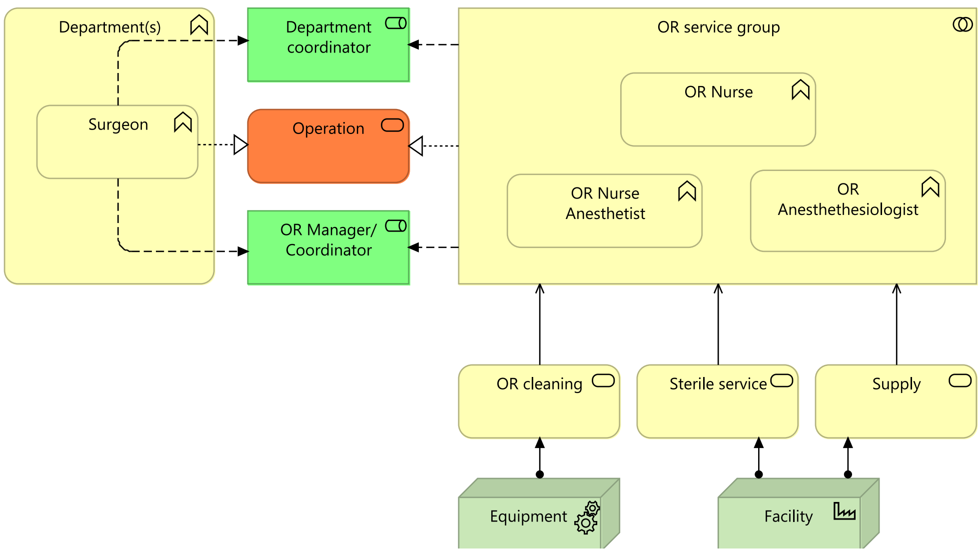


Figure 6.9: A view of business relationships among different departments and stakeholders of OR-WPS modelled in ArchiMate® language

[24]Source: Alex Macario (2006), Are your hospital operating rooms efficient? - A scoring system with eight performance indicators [Mac06]

6.4.3 Information Systems Architecture

Digitalisation can help achieve reduction in costs, fewer errors in operation, and overall workforce job satisfaction. As shown in figure (6.2), a PESTLE analysis conducted in the background identified an opportunity named *computer simulation*, which has the potential to improve a set of KPIs such as *cost*. A model is proposed, as shown in figure (6.10), in search of a possible solution in the form of an *information system* to support the business drivers. The relationship is that a “digitalisation of the process and decision" is *associated* with creating a computer simulation. It is in turn *associated* with “cost reduction". A *course of action* called “digital transformation" will aid in *realising* the “cost reduction". A business requirement, namely, “create OR-WPS simulation" was used as means, which in turn would *realise* strategic capability “OR-WPS digital twin simulation"[25]. Similarly, the states “baseline" and “target—digital twin of enabling processes" *realise* both “digital transformation" and “create OR-WPS simulation", respectively. Similarly, “target—digital twin of enabling processes" would help *realise* strategic capability “OR-WPS digital twin simulation" as well.

The architecture model in figure (6.10) has focused on only *drivers*. However, in the following section (6.5), focusing on the how question, the model is explained in detail. Objects such as “outcome", “work package", “business actors" and “stakeholder", which have a *realization* or *association* relationship with the state of “baseline" and “target", are described.

[25]Note: Independent from specific implementation type

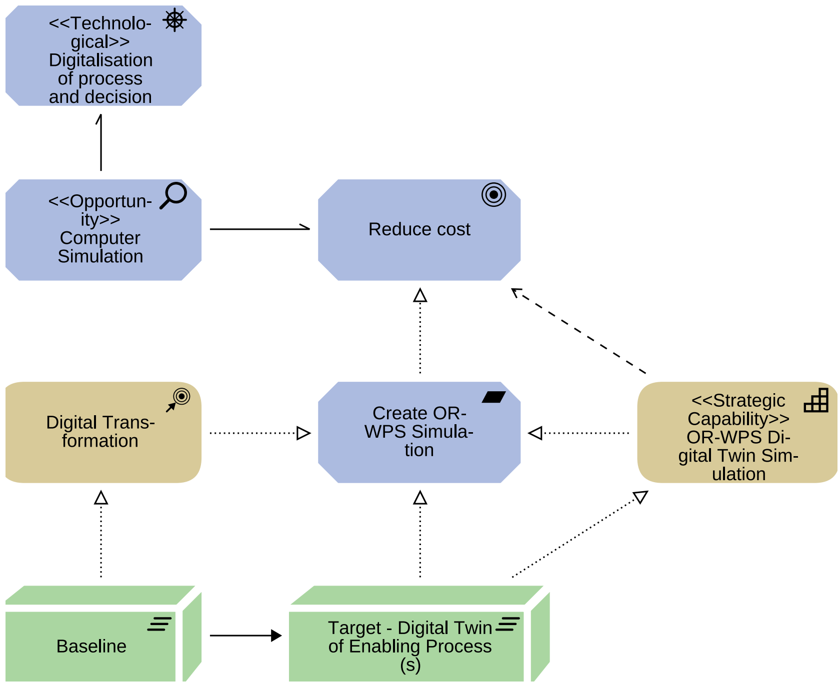


Figure 6.10: Mapping from a business drive at the top-left, to business capability at the middle-right, to planned states (plateau) at the bottom in ArchiMate® language

6.5 Logical Level - How

The *logical* level sets the foundation what the *ultimate* solution would seek and to address the *how* question. The logical level focuses on mainly two views: project architecture, as detailed in section (6.5.1), and data architecture, as explained in section (6.5.2)[26].

6.5.1 Project Architecture

A *project architecture* view systematically presents the logical creation of a simulation software. It begins with the current reference state of the OR-WPS enabling process, which is actually without any simulation support. This state is known as the “baseline", as shown in figure (6.11). Therefore it is reasonable to devise a research work, “simulation PoC", which could eventually create the “process map" and “Lerncockpit" deliverables. These *deliverables* should reproduce the current state of the OR-WPS

[26]Note: Given the relatively narrow focus of the study, further information on the business, information system, and technology was not available for this level of analysis.

business process maps[27] and are part of the “transition" state. In order to achieve the “target" state, the research work should create the computer-simulation application, namely, *ServiceSim* OR-WPS. The gaps among baseline–transition–target are illustrated in figure (6.11). The benefit of such an architecture is to clarify in front of the project stakeholders whether it makes logical sense and is therefore usually created at the logical level of EA.

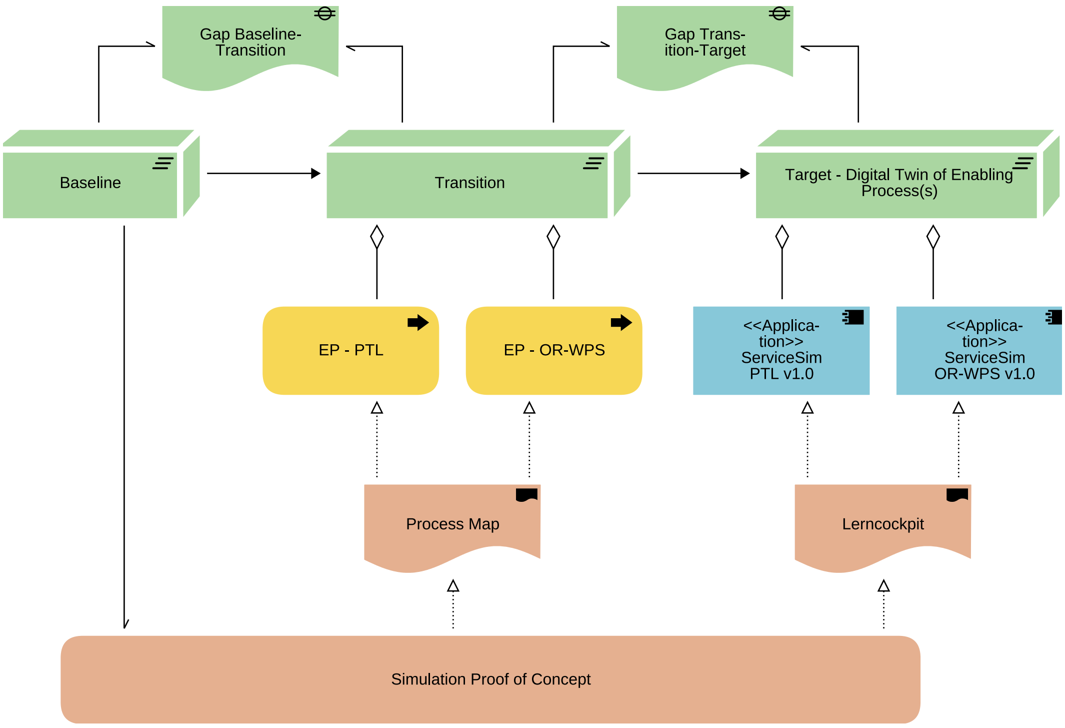


Figure 6.11: An overview of Transformation Architecture, its inputs to create a transition from Baseline Architecture to Target modelled in ArchiMate® language

6.5.2 Data Architecture

In order to create an accurate data-driven computer simulation, whether as-is or to-be state of the (enabling) process, the fragmented business objects and data objects used by the OR-WPS business process must be identified and evaluated; thereafter, improvements must be implemented and employed for appropriate use. It is critical as their knowledge would generally be missing, ownership would be unclear, and the

[27]Note: PTL is beyond the scope of this work.

update would not be performed. Without proper understanding and implementation of *data architecture*, the application of advanced (future) themes such as big data, business analytics, predictive analytics, and business intelligence cannot realise their potential benefits. In this regard, data architecture can be defined as in the following definition (6.26).

Definition 6.26. *Data Architecture*

> *"Data architecture is a blueprint for how data is stored and flows across the enterprise over its life cycle." [FF18, p. 91]*

Instead of setting *enterprise-level* scope in this study, an example of applying data architecture on OR-WPS was showcased[28]. Background information regarding the approach in this study can be found in Fleckenstein et al.[29]. A few questions that were addressed in this study can be listed as follows:

(a) Is there any relevant data from a (previous) study before developing the simulation model? Who is the owner of the data? How could the data be used for the purpose stated herein?

(b) Do this data identify any personal information? Are there any legal requirements to fulfil before the use of this data?

(c) What are the quality requirements of the data? In which business process are the data being used? How would the data be used in this study?

Based on the aforementioned questions, a research process was followed to acquire the data while ensuring that no personally identifiable information would be collected or used in this study. In the beginning, an identification of *master*, *transactional*, and *reporting* data categories were considered in this study. *Reference* and *metadata* categories were not considered. In addition to data models and objects, a viewpoint worth considering was their logical relationships with the applications, business processes, and physical infrastructures. This viewpoint yields results that are of relevance to this study, as illustrated in figure (6.12). On the basis of the approach

[28]Note: Light-version application of data architecture on another enabling process PTL is already reported by Phadke et al.[Pha+15] but with less rigor. In the case of OR-WPS in this study, it was applied more formally.

[29]Source: Mike Fleckenstein et al. (2018), Modern data strategy [FF18, pp. 91-105]

and the aforementioned questions, *business actors* including a nurse, nurse anaesthetist, and surgeon were identified; they are probably the most essential in the data architecture. The OR-WPS process owners in the hospitals were consulted to check if any data model-related projects were created in the past. Owing to the unavailability of models for computer simulations, a customer-journey approach was followed for modelling in this study. Consequently, identifying the *data objects*—essentially logical representations of data that can be processed using computational hardware— was essential. At the application layer, data objects represent business objects.

The aforementioned viewpoint helped comprehend the relationship among the master data “OR Nurse", the transaction data “Number of OR Nurses", the enabling process OR-WPS, the intended application component “ServiceSim OR-WPS", and the hardware used to run the ServiceSim simulation “Lerncockpit". The relationship among them is as follows.

- *Responsible* relationship between “OR Coordinator” (individual) and “OR Nurse" (master data)
- *Data-Access* relationship between "OR Nurse" (master data) and “EP–OR-WPS" (business process)
- *Serving* relationship between “SeviceSim OR-WPS (application component)" and “EP–OR-WPS (business process)"
- *Realization* relationship between “Lerncockpit" and “SeviceSim OR-WPS" (application component)
- *Specialization* relationship between “Number of OR Nurse " (transaction data)" and “OR Nurse” (master data)"

In addition to the application layer, if measurement devices such as sensors were available at the physical infrastructure layer, they could help create and manipulate these data objects. Thus, the data objects such as the availability of workforce (staff) and the number of operating rooms were also identified (but not shown herein). The reporting data objects such as productivity, quality, cost, and customer satisfaction were also planned to be measured. By providing suitable logical views, one can effectively guide a *physical* level.

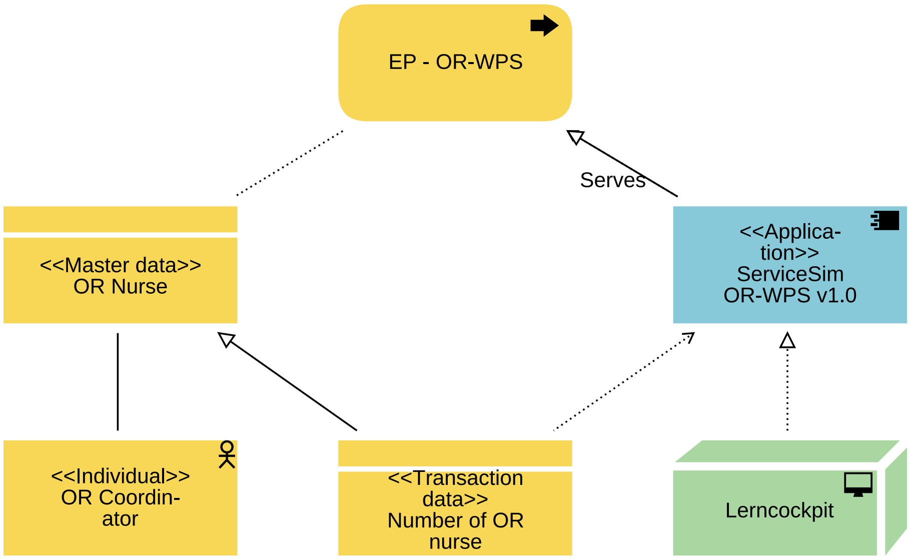


Figure 6.12: View logical relationships among application, business & data objects, actor and physical hardware. Only the elements relevant to this study are modelled in this view in ArchiMate® language

In order to perform the calculation of *customer satisfaction* based on the heuristic proposed in section (4.2.4.2), a viewpoint from a software-development perspective would be needed. To this end, the data architecture could deliver a logical relationship among the *business actors* for which the calculations are to be performed, customer-satisfaction *transaction-data*[30] object as an output of the computer simulation and the corresponding *master data*[31] from the factor analysis as reported by Hastreiter et al.[32] of BELOUGA project. Figure (6.13) illustrates the relationship among the master data based on factor analysis, which form the input for software development; transaction data, such as customer satisfaction; and the multitude of business persons such as OR nurses. On the basis of the performed analyses, as detailed in this section and previous sections, the investigated views in terms of business, information system, and technology are presented in the following section (6.6).

[30] Note: Customer satisfaction is transactional; apart from these factors, a measurement performed during the simulation outputs absolute customer satisfaction.

[31] Note: The earlier data are classified as master data because this would not alter for the simulation project. In the event of any new study for which the outcome would be a different percentage contribution of the factors, it would constitute the new master data for the study.

[32] Source: Stefan Hastreiter et al. (2015), Benchmarking-Studie OP-Personaleinsatzplanung [Wor+15a, pp. 231-235]

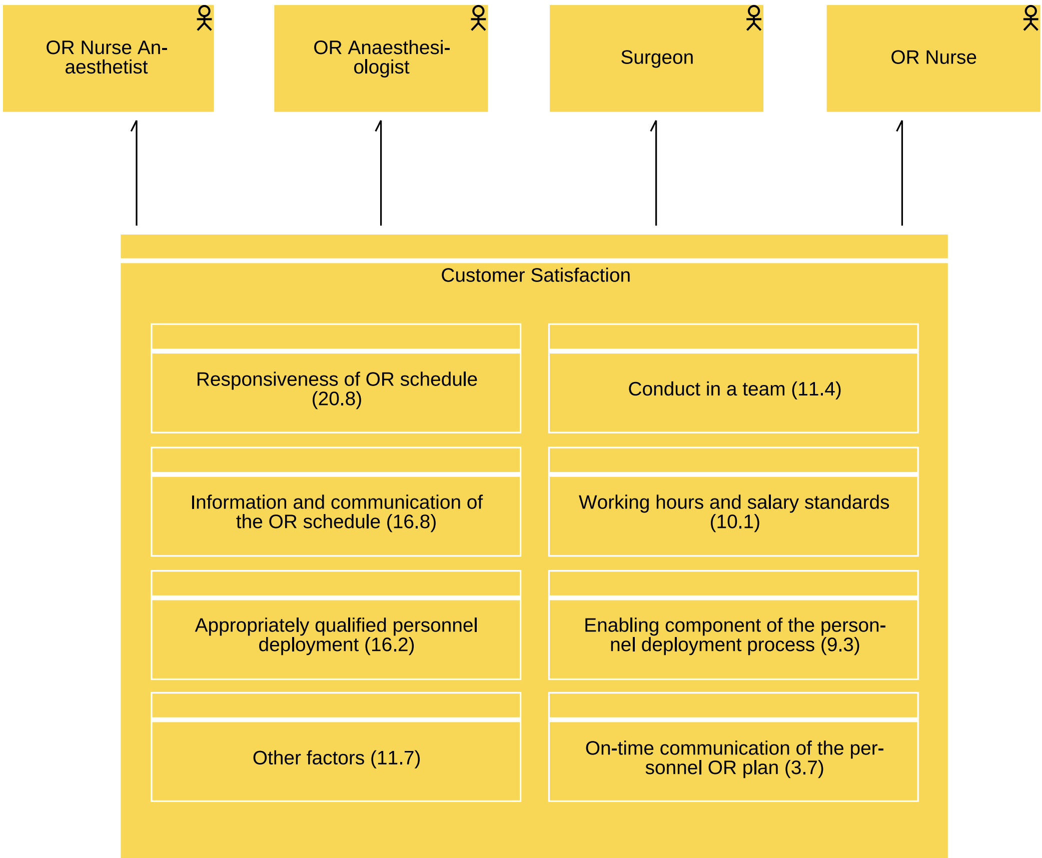


Figure 6.13: View of influencing factors of the identified value dimensions on customer satisfaction using *factor analysis* in the ArchiMate® model for OR-WPS enabling process with values in a comma is as a percentage (%).

6.6 Physical Level - With-What

At the *physical level*, the scope addresses concerns raised and requirements identified in the contextual (6.3), conceptual (6.4) and logical (6.5) levels. At the physical level, a mapping from previous levels would result in, for instance, a web server or a physical IT application, as described in this section. The following subsections present a business view (6.6.1), an information-systems view (6.6.2), and a technology infrastructure view (6.6.3).

6.6.1 Business View

In a *business* view, the focus would usually be on the use case presented in figure (6.14). The use case describes that an OR scheduler/coordinator or an OR manager would use *Lerncockpit*. Lerncockpit is similar to the cockpit used in an aircraft, and the hospital may refer to it as a business concept. The *service* of Lerncockpit can be used via an *interface* to perform a *computer simulation* of the OR-WPS business process to obtain outputs such as *classical* as good *value*-based KPIs.

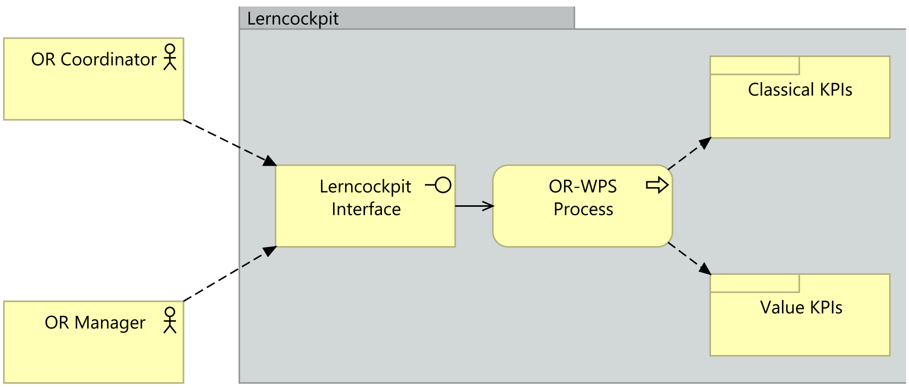


Figure 6.14: Lerncockpit use case modelled in ArchiMate® language

6.6.2 Information Systems View

Whereas Lerncockpit is essentially a business concept, as mentioned in section (6.6.1), a *ServiceSim* OR-WPS application is physically implemented. An impact analysis based on the data objects, business processes, and application components, as shown in figure (6.15), reveals the relationship among them. Furthermore, the analysis affords insights into the data objects involved in the OR-WPS business process and which application component finally processes these objects. The benefit of such a view was that it helped identify the data sources to provide input/output for the target design of the simulation.

This view shows that a new *business activity*, known as *service simulation*, is created in the top lane called the *business process*. The OR scheduler or coordinator would perform the activity to evaluate the OR-WPS by using specific input data. The data are defined in the middle lane called the *data object*, which is mainly composed of *transactional data* such as the replacement staff or number of ORs. The bottom lane, known as *application component* has a new computer simulation (or IT) application called *ServiceSim* OR-WPS v1.0[33]. All these elements are interconnected with certain relationships.

From an information-system (IS) perspective, it would be interesting to define which types of value would be delivered by the *ServiceSim* OR-WPS. As a starting point, a view in a SWOT analysis was created, as shown in figure (6.16)[34]. It shows that the implemented the performance of the simulation software can be evaluated if the experience with the user is a success, the weakness is minimised, and opportunities are further exploited. This view can help further improve Lerncockpit.

[33]Note: Version v1.0 implies the production-level version of the IT application.
[34]Note: An *assessment* is exhibited as a *magnifying* glass.

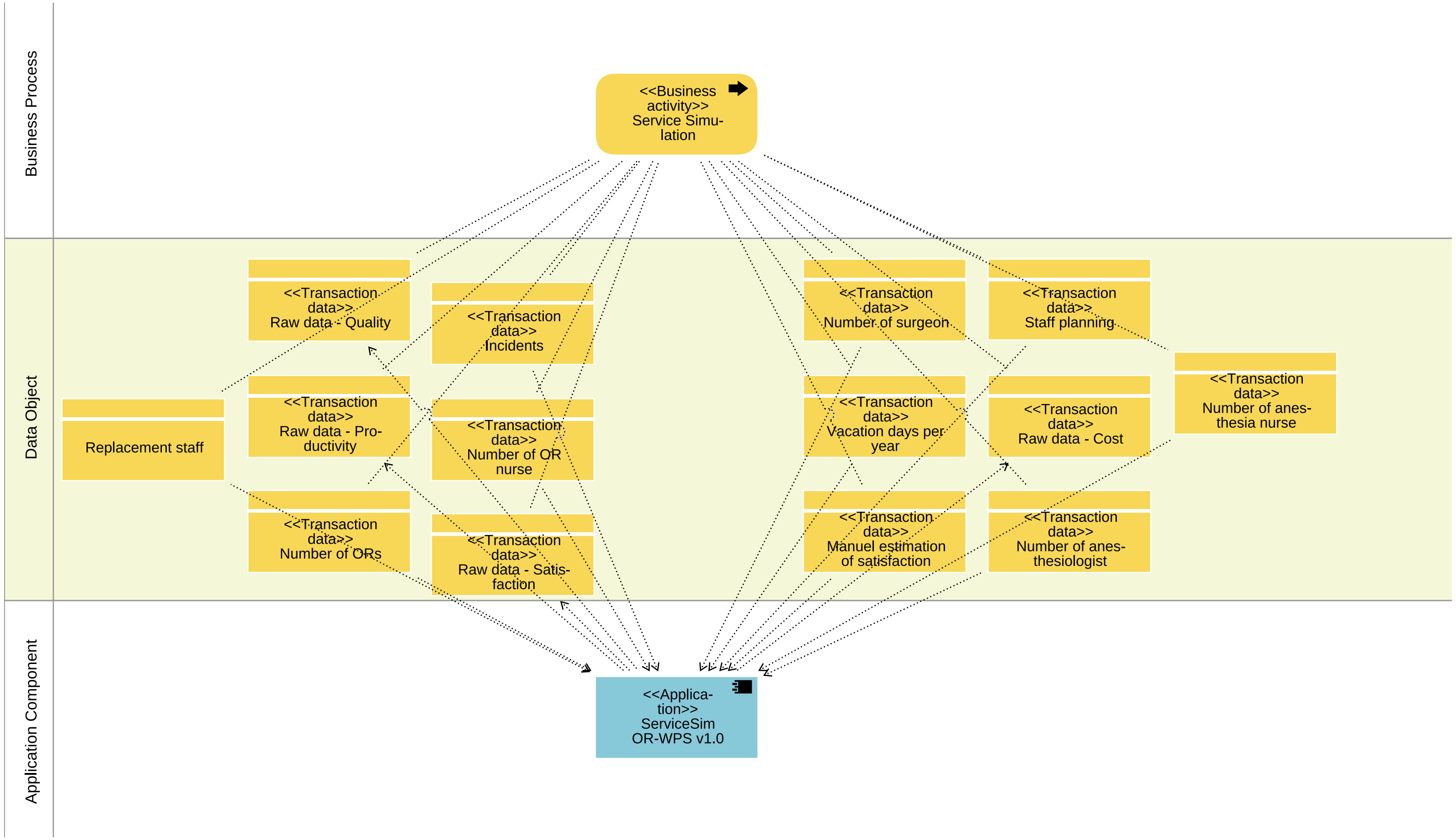


Figure 6.15: A focus on data objects and their relationship with business process and application components is modelled in ArchiMate® language

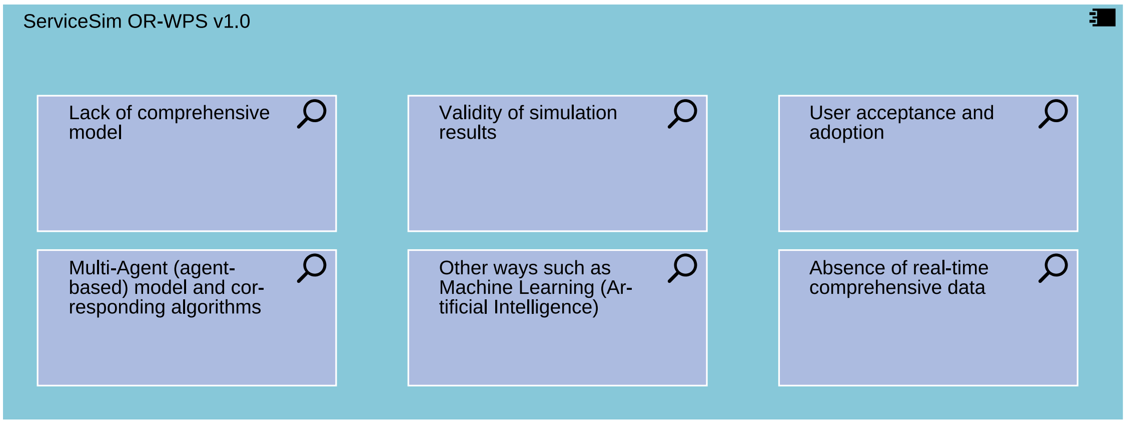


Figure 6.16: A SWOT analysis of the ServiceSim OR-WPS application component modelled in ArchiMate® language

6.6.3 Technology Views

The purpose of the *technology view* is generally to answer the questions related to types of physical infrastructure elements needed to deploy an IT application comparable to *ServiceSim* OR-WPS. Given the research focus of this study, only a high-level model, as shown in figure (6.17), is presented herein. It depicts the interaction among infrastructure components in a typical IT domain such as operating systems, network, firewall, and network service. It also shows that a simulation program can potentially be deployed in the existing hospital IT application server and coexist with other IT applications supporting core healthcare processes. In the future, TOGAF Technical Reference Model (TRM)[35] can be used to further refine the technology view. It can offer a reference model of generic platform services and technological components. The TRM is a set of architectural and solution building blocks that could eventually provide the platform for scalable and interoperable infrastructure applications of DT simulation.

[35]Source: Open Group (2017), The TOGAF® Technical Reference Model (TRM) [Ope17]

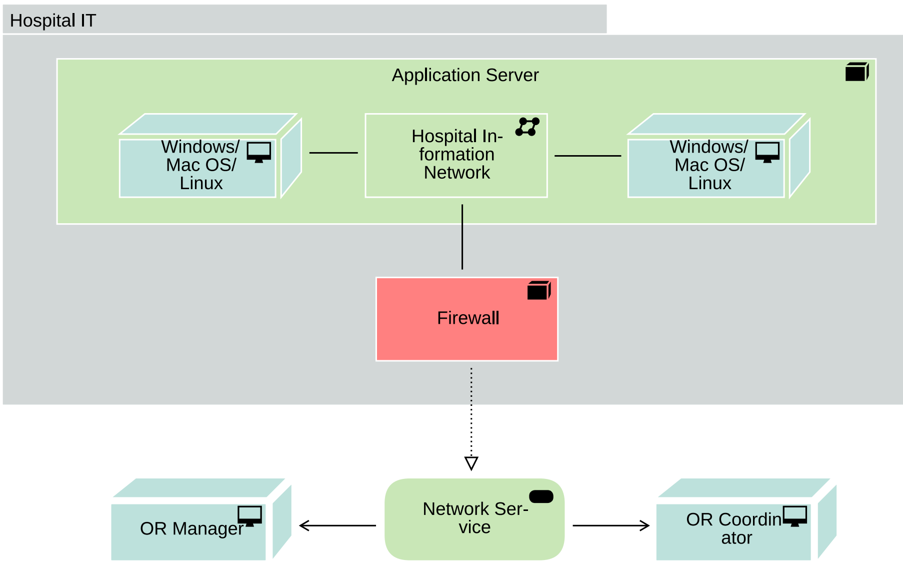


Figure 6.17: A Digital Twin conceptual ArchiMate® model provides computer simulation capability specific for OR-WPS of a typical hospital

6.7 Outcome

On the basis of the results as well as the experience gained while developing an enterprise architecture in this study, the following conclusions can be drawn:

(a) EA focuses on supporting an organization undergoing business or technological changes. These changes usually reflect on their IT landscape. By applying the concepts of EA, the development of simulation from inception to physical manifestation could be managed appropriately. The stakeholder expectation could be better understood, and the positioning of the simulation tool could also be effectively explained. The OR-WPS enabling process can be implemented in the multi-agent simulation with (intelligent) agents.

(b) The creation and alignment among different modelling domains, namely, business, data, application, and technology, can be adequately managed in an EA tooling. For modelling in different EA layers, ArchiMate®, for business process modelling BPMN were used. For software implementation UML, and for multi-agent modelling, *UML state machine* would be likely be the most suitable; these aspects are discussed in previous sections.

(c) Specifically for information alignment in this study, such as *validation* with the business stakeholders, presentation programs are more suitable as compared to models created in a language such as ArchiMate®. There still exists a gap concerning direct translation standards between presentation programs and formal architecture language and vice versa.

(d) The levels and their deliverables are not always created in a strict sequence. For instance, the process maps for OR-WPS were delivered in the “business process" section of the conceptual level. In contrast, it was mentioned as a deliverable in the logical level “project architecture". There are no strict rules regarding a fixed sequence to follow in case of EA. Instead, the views were mostly created in the decreasing order of their ease to develop and plausibility.

7 Conclusion

This chapter summarises this study, its key findings, and their practical implications in hospitals in particular and healthcare services in general. Furthermore, the digitalisation developments relevant to hospitals—influencing almost every aspect of their business ecosystem—are presented. A section summarising the strengths, weaknesses, opportunities, and challenges associated with this study is included. Based on the experience and insights afforded by this study, a foreword is provided for future proposals that will potentially benefit healthcare services and help advance the state of the art.

7.1 Epilogue

This study aimed to demonstrate the implementation of a multi-agent simulation model of the OR-WPS enabling business process for a specific hospital. Both the conceptualization and the implementation of the computer simulation of the OR-WPS enabling process were conceived based on actual data collected in several large hospitals in Germany and the USA. OR-WPS was selected in this study because it supports the most cost-intensive and profitable aspect of the ORs in hospitals. Work sampling was employed to collect statistical input data for future simulations, followed which the standard distribution patterns for OR scheduler activities in a hospital. A survey-based comparison highlighted the commonality and differences between two hospitals in different geographical locations. A content analysis was performed to investigate the collected data from a different perspective. Creating the EA views of OR-WPS paves the way for a new line of future research. This will potentially aid the development of a DT of hospital business processes based on computer simulation.

7.2 Outline

The preceding chapters, particularly *solution approach and method* (4) and *result analysis* (5), focus on the OR-WPS enabling processes of hospitals from Germany and the USA from different viewpoints; they present the results based on scientific research methods. The purpose of applying several methods for analysis was to advance our understanding of their application on enabling process. This blend of different viewpoints can reinforce the users' trust in computer simulation as a viable approach to building a DT of the business processes in hospitals. Therefore, qualitative and quantitative analyses were used to showcase how relevant knowledge can be discerned from the process data and the results from this work reused in any future research or industry projects. To reiterate, the primary focus of this study was to conduct a literature review followed by modelling and simulation so as to ultimately create both “verified and validated" simulation model of OR-WPS. Qualitative and quantitative analyses afforded additional insights through collected data on the OR-WPS business process. The results from the data could potentially be reused in training machine-learning (ML) algorithms, for example, for supervised learning. This study entailed a systematic use of an EA management framework to address the research problem.

As shown in figure (7.1), the research methods had a *primary* and a *secondary* area of focus. The primary focus was on using (semi) systematic literature review (SLR) and multi-agent simulation (ABMS/MAS) and realising them by using different software. The secondary focus was on applying qualitative/quantitative methods via job shadowing, survey, work sampling, and EA management as advanced work. Specifically, during the contextual, conceptual, logical, and physical development of ServiceSim OR-WPS, this study devised a chain of procedures, modelling, and programming languages, which can be further subdivided into their respective types, as shown in figure (7.2). The practical concepts employed in this study have been reported in the literature in a fragmented manner, scattered over varied research focuses. The uniqueness of the present study is in realising a concurrence of many such practical concepts in one value proposition and providing a structure for future use. The previous sections (2.3.1), (2.3.2) and (2.3.3) in chapter (2) focus on the reported findings by authors from relevant literature, which have either solved the same or similar research problems or have applied the procedures in a completely different domain than healthcare but have substantial contextual commonality.

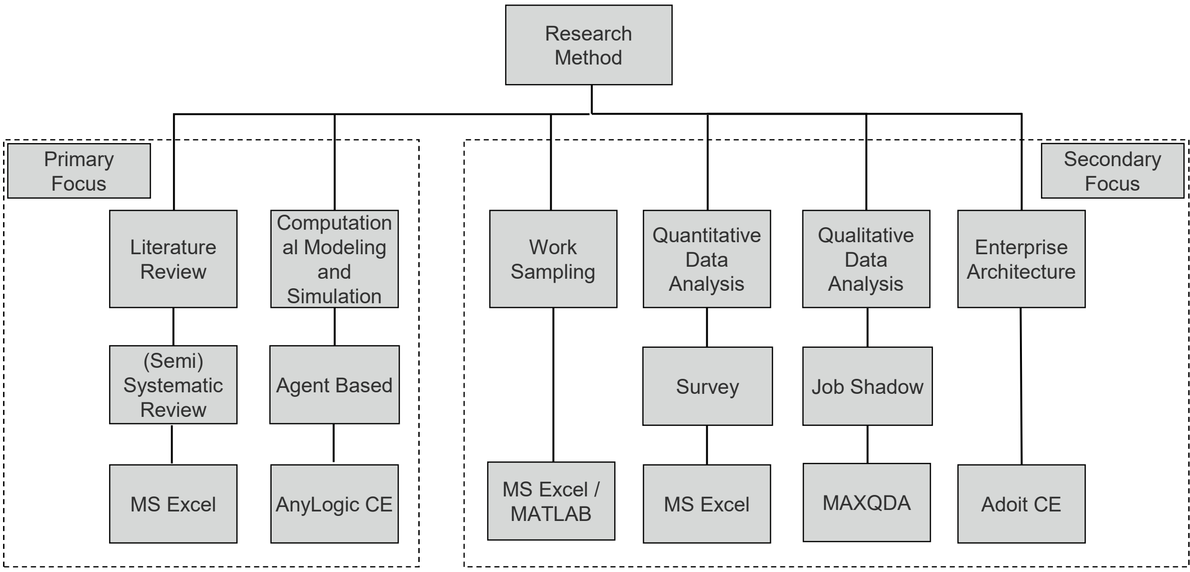


Figure 7.1: Tree diagram providing an overview of focus, approach and research method, along with an in-depth analysis up to information technology applications to obtain the results reported herein

7.2.1 Key findings from the research work

The demonstration of the computer simulation using ABMS/MAS is particularly noteworthy from a research perspective. A novel heuristic was conceptualised, implemented, and validated to measure customer satisfaction and classical KPIs such as productivity, quality, and cost in a simulation. The four key findings are summarised here.

Key Finding #1: At present, there is no one-size-fits-all framework that can provide the essential needs while creating a computer simulation of operating room business processes on its own. Numerous management and software frameworks are needed to build appropriate DTs based on computer simulations.

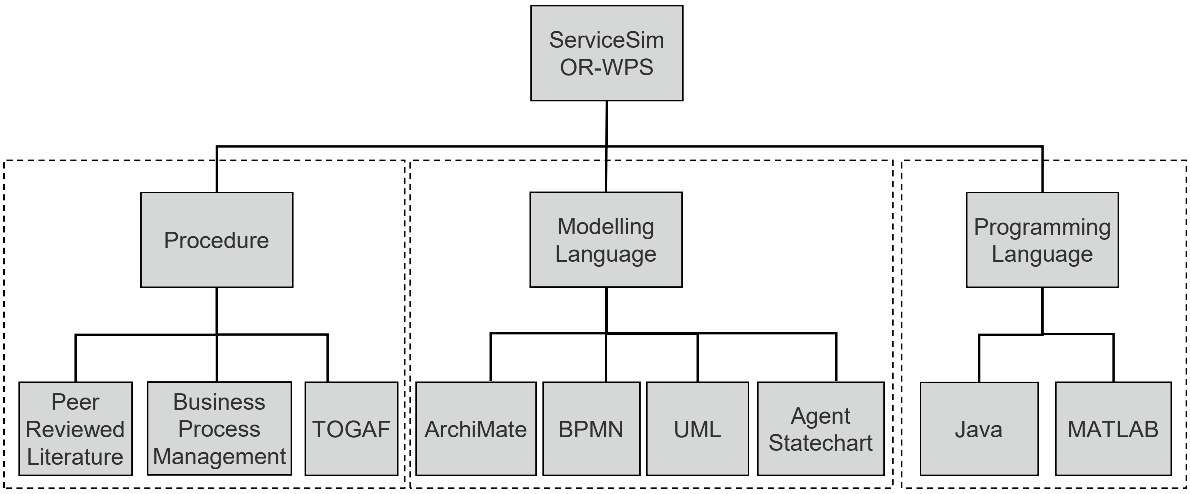


Figure 7.2: Tree diagram providing an overview for ServiceSim OR-WPS modelling and simulation toolchain

A reference process of OR-WPS was discovered in this study[1]. A simulation model based on the documented business process needs translations in a software programming language before realising the corresponding multi-agent simulation. The critical finding from the perspective of the process stakeholder engagement is as follows:

> *Key Finding #2: The business processes are often undocumented and not digitalised at hospitals. Collaboration, cooperation, transparency, and trust are prerequisites for the digital transformation of the business processes.*

The process areas such as workforce planning and scheduling and patient-transport logistics may be linked to the primary (core) process of providing medical treatment for patients. While there have been several prior studies on the performance of the primary process itself, no concrete modelling and simulation-based research toward an integrated process improvement has been reported. The present study mainly focused on workforce/staff schedules but should be coupled with *case scheduling*,

[1] Note: In addition to OR-WPS, a reference process and ABMS/MAS of PTL was also previously developed by Phadke et al. [Pha+15].

as mentioned by McIntosh et al.[2]. In the current simulation model, the customer satisfaction calculations are based on a proposed heuristic and weights in the surveys. However, they must be further validated, and this approach must be improved as needed. The computer simulation can aid in answering the questions concerning economic advantage of outsourcing the operational activities of ORs. It can also help analyse the financial benefit, for example, cost savings and business benefits such as increasing the quality of service and flexibility of the services, which would form the basis for the decision as to whether to outsource.

7.2.2 Key findings for the practice

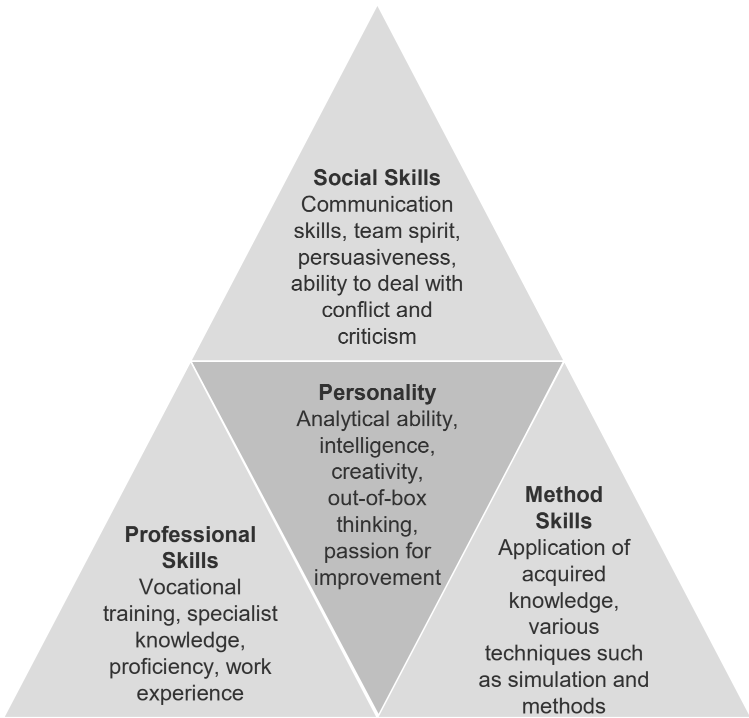


Figure 7.3: Ideal set of (non-exhaustive) skills required to utilise the possibilities offered by digital-twin based process improvement based on the field observations and interviews

[2]Source: Catherine McIntosh et al. (2006), The impact of service-specific staffing, case scheduling, turnovers, and first-case starts on anesthesia group and operating room productivity - A tutorial using data from an Australian hospital [MDE06]

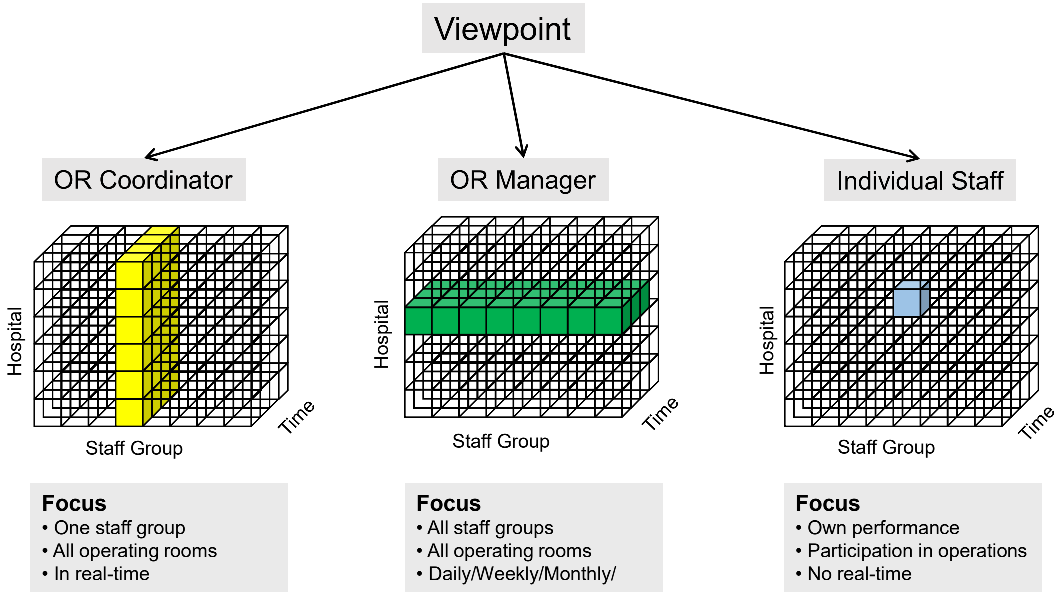


Figure 7.4: Overview of the viewpoints of stakeholders of ServiceSim OR-WPS with their focus to support their work at a hospital

Information technology can be a great enabler to digitalise the business process; however HITL is still indispensable in the healthcare domain. Because the human decision process cannot be digitised yet, its role in supporting the enabling process is a critical success factor (CSF). People with appropriate skills and work experience, as indicated in figure (7.3), is currently key to planning and scheduling at ORs. Therefore, in order for it to be successful, any digital transformation of the business process must consider the human factor. Possible options are the use of AI, as mentioned by Spyropoulos[3], focusing on planning and scheduling in the hospital environment.

Key Finding #3: Healthcare provision still concerns a human-in-loop based decision-support system embedded in the sociotechnical healthcare-service environment. The healthcare service domain must choose and implement appropriate digitalisation steps.

The results of the simulation study in the present work was suitably validated. In the experiments, the approach was to perform as many randomised experiments as

[3]Source: C. Spyropoulos (2000), AI planning and scheduling in the medical hospital environment [Spy00]

possible; this is the gold standard of scientific research. Langley et al.[4] attempted to address the question of the general applicability of knowledge gained in the other domains and concluded that effective changes in the other domains are not possible without ample information gained through experience, knowledge, and intuition of the subject matter experts who grapple with the problem on a daily basis. Owing to the limited scope of this study, there were sets of experiments that could not be conducted and validated. Only the limited viewpoints of the simulation modeller, the OR coordinator/scheduler, OR manager, who are steering the OR schedule or deploying the workforce members in the computer simulation, could be considered in the experiments, as shown in figure (7.4). Evidently, simulation can perform validations on a fraction of the possibilities. Therefore, the design of experiments (DoE) becomes essential as it may help future studies maximise the learning from models in the minimization of input efforts. The key finding in this regard is as follows:

> *Key Finding #4: The simulation results are non-generic, not "mutually exclusive and collectively exhaustive". In order to use the results in the real world, more experiments that consider several real-life scenarios are needed to build trust in the model.*

7.3 Ongoing Developments

During the development of multi-agent simulation, it was impossible to collect and use data from any sensor in the hospitals, as this was out of the research scope. The ongoing 4th wave of digitalisation in industry, also known as Industry 4.0, is also being embraced by the healthcare service sector, which is conducting its tailor-made digital transformation. For instance, Rodic[5] described *Industry 4.0* as opening a new simulation modelling paradigm. The use and integration of the technology offerings, namely smartphones and their applications, wearable devices, robotics, are already being used in one or other parts of the (observed) hospitals. On the one hand, the pace with which this is happening in healthcare is not adequate as compared to other sectors. This may be attributed to several concerns, such as those associated

[4] Source: Gerald Langley et al. (2009), The improvement guide - A practical approach to enhancing organizational performance [Lan+09, p. xxiv]

[5] Source: Blaž Rodič (2017), Industry 4.0 and the new simulation modelling paradigm [Rod17]

with patient–employee data, human factors, potential loss of jobs due to automation, business–cultural issues, and constraints due to EU data-protection law. On the other hand, the prevalence of new technologies, business models based on the sharing economy, and ever-increasing human expectations from digitalisation can lead to opportunities as well challenges due to the application of multi-agent simulation or, in the future, AI in healthcare provisioning.

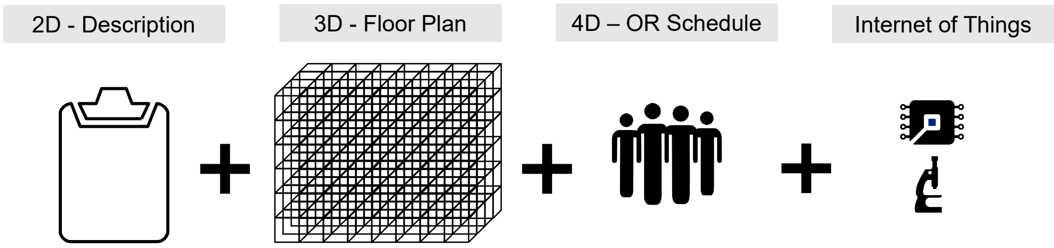


Figure 7.5: Proposed DT model of a future hospital. Proposed DT model of combining the hospital asset data in 2nd/3rd dimensions for textual descriptions and floor plans, 4th dimension for ORs schedule data, and further for sensor data from about human-machine to achieve a DTof the hospital

One can *combine* the two-dimensional information with a three-dimensional hospital floor plan and OR schedule representing the fourth dimension connected through the IoT and potentially create a real-world DT of the OR-WPS process area, as shown in figure (7.5). Haag et al.[6] reported a PoC of the DT. It can be used in multi-agent simulations for predictive analytics or machine learning to create future predictions using large amounts of data. The findings by Croatti et al.[7], who studied the integration of agents and DTs in healthcare support this idea. A decision support based on DT simulation by Pires et al.[8] also reinforces this vision. In addition to the aforementioned works, an investigation on the role of the IoT and DTs in the healthcare digitalisation process was reported by Patrone et al.[9]. Finally, with regard to actual implementation, Karakra et al.[10] realised a predictive simulation-based DT for patient

[6] Source: Sebastian Haag et al. (2018), Digital twin – Proof of concept [HA18]
[7] Source: Angelo Croatti et al. (2020), On the integration of agents and digital twins in healthcare [Cro+20]
[8] Source: Flávia Pires et al. (2021), Decision support based on digital twin simulation: A case study [Bor+21]
[9] Source: Carlotta Patrone et al. (2020), The role of internet of things and digital twin in healthcare digitalisation process [Pat+20]
[10] Source: Abdallah Karakra et al. (2019), HospiT'Win: A predictive simulation-based digital twin for patients pathways in hospital [Kar+01]

pathways in a hospital.

7.4 Evaluation of the Work

This study notably focused on areas that have been relatively less explored. It focused on healthcare enabling/supporting business processes. By successfully explaining “why" the focus must be on these aspects, key stakeholders were interviewed in Germany and USA. The data were collected concerning their ORs business models, business processes, challenges, opportunities, interests, and day-to-day work so as to answer the research questions. A multi-agent simulation of the real-world process was implemented, followed by the design, development, and measurement of classical and value-based KPIs to predict the process performance using Lerncockpit. A semi-structured literature review (SLR) supported all these aspects. In addition, this study remarkably afforded a process-level visualised comparison between the OR-WPS at German and American hospitals based on actual data from the field. The *interviews* were undertaken with different roles/stakeholders, and the following queries were posed in an *open-ended* manner: “which enabling process are the most important for the hospitals?" and "what is the current state of the OR-WPS?". This implies that the questions were not focusing on a specific type of problem but sought to identify and clarify direction for in-depth exploration and subsequently build a research relationship to acquire qualitative and quantitative data for both customer surveys and process simulation. The survey was designed based on the open interviews and was intended to obtain further insight in a quantitative form. The inherent weakness of the survey remains—the questions being of limited relevance to the interviewee as well the lack of tailoring of the questions designed targeting German stakeholders for use in the American context. Some questions were found to be not interesting, for instance, in Missouri hospitals as compared to those in the German hospital considered in this study. As the activities and tasks performed within an enabling process at the hospitals cannot be generalised, there is still a need to recruit and review more interviewees. In case of a favourable response, the results may be collated and analysed, while preserving the confidentiality, so as to establish their applicability in other hospitals. Therefore, the generalisation of the survey questions is time consuming. As the sample sizes from both German and American hospitals were sufficiently large, this study estimated the significance of the findings of the comparison by using statistical techniques; this is a remarkable achievement. EA was used to propose an advanced work to manage the future digital transformation.

The most attractive feature of ServiceSim OR-WPS simulation program is the processing time. As regards real-time application and relevance, the results are obtained relatively fast and can be helpful in decision support. Both the pace at which the final results were obtained and their quality are essential in the healthcare domain. As aforementioned, similar to studies on space exploration, military, and power grids, healthcare is supposed to be an HRO. A computer simulation used to convince the operating room management about an anticipated bottleneck in the available resource to run the surgeries with cost successfully, productivity, quality, and satisfaction considerations should have minimum variability in the outcomes; this is also the case with the input estimates. The *gamification* as a technology trend to offer training to operating room schedulers in a safe environment to perform experiments is where the ServiceSim OR-WPS could find its first real-life application and subsequent adoption. In contrast, the concept of *technology adoption* is beyond the scope of this study. However, there are cases wherein processing time may be highly relevant. It happens when the simulated system is too complex, when there are many replications to be performed, or when the response time is critical, for example, in military applications. There are also cases wherein the response time is not remarkably important. However, higher-quality results are required to improve the presentation of the results, for example, to convince managers regarding the events that may result if no particular action is taken. When such situations arise, reducing the variability of the estimates is worthwhile.

One of the limitations of this study finds its origin in the domain of interest itself, namely, *healthcare services*. Medical treatment and its relevant sub-branches are notably *human-centred*. DTs of healthcare services that can simulate, monitor, and provide decision support could improve patient safety. It can also provide better access to critical information, provide a platform for interdisciplinary communication among stakeholders, and let medical staff concentrate on their critical task of providing care to patients in need. The limitations concerns the ability of a simulation to mimic the reality given the levels of approximation performed in modelling and the range of solutions it could provide for the given problem. Through good collaboration among DT users, simulation modellers, and decision makers in healthcare, one can begin from a “imperfect" model and iteratively approach a “realistic model" in time. The proposition made in this study is to accept its outcome as “a part of the bigger picture". Another limitation concerns the effort needed to change the underlying simulation program. In this simulation, it is not foreseen that immediate changes in the implemented software are possible based on the results (i.e. the KPIs). From the perspective of programming, this is possible; however, as regards the efforts, it needs intermediate to advanced skills in writing computer codes or programs. A low-code multi-agent simulation platform could hold tremendous promise in the future.

7.5 Future Proposals

Although ambitious and challenging, this study could not fulfil a few objectives, and these are to be pursued in future research. These objectives are presented in the following subsections.

7.5.1 C2E Integrated Simulation

The business process and its simulation scoped only one or two enabling functions of the healthcare provider. The thought process behind core to enabling (C2E) is the creation of a DT of the hospital in the form of an *integrated system* of core (primary) and enabling (secondary/supporting) process scaled models and simulation. Multi-agent simulation is not the only approach to creating a DT and decision support system. Alternative approaches would include investigations based on the knowledge acquired in this work concerning aspects such as the enabling business processes; design, implementation, and measurement of value-oriented KPIs; simulation method and relevant experience gained; and role of the survey in the value-based measurement.

7.5.2 P4S Service

“Application follows Process" vs "Process vs Application"—the simulation model was developed using an observed benchmarked enabling business process, and simulation software was developed with customization for this purpose. To examine another business process in healthcare, the same procedure will have to be repeated. It will be attractive for future applications if the business process can be automatically documented with minimum customization in the simulation. Process mining and automated code generators are potentially applicable in this regard. On the contrary, if a standard simulation software could simulate most of the business processes as a standard, it can reduce future costs and make it an attractive proposition for practical application. A direction for investigation in this regard is the use of process mining to create process models, as suggested by Mans et al.[11] and Fernandez-Llatas[12]. Process mining could be used to visualise and comprehend the variations of enabling processes and deliver fact-based process management. However, because the OR-WPS is not adequately documented and is not incorporated in most enterprise software, developing an “as-is" variant of it is remarkably challenging. In a nutshell, this enabling process does not have (sufficient) event logs in the hospital information system. Future research could extend our approach of process modelling through mining techniques. The process modelling approach adopted in this study is based on interviews with the key stakeholders and the information available in magazines, manuals, or annual corporate reports. As compared with the strategic level, at the tactical and operational levels, the business process has many variabilities. The application of process mining could disrupt how improvements could be realised via process simulation, as process mining may partially replace simulation.

7.5.3 Human Factor

The significance of human decision making in the healthcare discipline is highlighted herein. In parallel to the possibility of introducing AI in the simulation models, a dehumanization in the medical process in varied aspects such as in performing diagnosis and prognosis, disease prevention, and even surgical procedures is possible in the

[11] Source: Ronny Mans et al. (2015), Process mining in healthcare [MvV15]
[12] Source: Carlos Fernandez-Llatas (2021), Interactive process mining in healthcare [FL21]

foreseeable future. This study identified that focusing on core healthcare processes rather than on optimising and improving the enabling business process would be more advantageous. However, several questions arise. Will it be efficient, acceptable, and not undermine the central role currently played by humans? How about actually building such a simulation model? What are their limits and the ways to prevent their incredible results, if any? Such questions are not considered in this study, and further research is warranted. Unwritten rules in an OR, which are logical arguments or course of action implied by tacit assumptions, are generally never documented but are present in organizational hierarchy (i.e. surgeons and nurses) and organizational culture and are practised by the personnel. These unwritten rules enable the personnel in OR-WPS to accomplish the daily, weekly, and monthly performance goals but can also lead to adverse effects. Not all the steps documented in the OR-WPS would be followed in practice. During the job shadowing (or participant observation), it was witnessed that several times significant/minor deviations from the prescribed business process occurred owing to the human factor. Owing to this vital characteristic, service provisions can be easily distinguished from production processes and are particularly challenging. It is impossible to capture, document, model and simulate the deviations; however, they can be handled using statistics in the model itself. Given the scope of the present study, it did not sufficiently explore the statistical aspect of this research problem, and this could be a subject of further literature review and model development. Current research such as the use of ethnography to quantify OR behaviour by Jones et al.[13] could afford relevant insights for value orientation. Further study could be pursued using and extending ServiceSim OR-WPS based on the mental model proposed concerning situational awareness (SA)[14,15], specifically the HITL or human factor in the healthcare domain.

7.5.4 Artificial Decision Making

The results obtained from the simulation of OR-WPS may be valid within its operating limits for the healthcare provider in the scope of this work. The results may or may not be valid for different healthcare providers, which can be small, medium, or large

[13]Source: Laura Jones et al. (2016), An ethogram to quantify operating room behavior [Jon+16]
[14]Source: Mica Endsley (1995), Toward a theory of situation awareness in dynamic systems [End95]
[15]Source: Mica Endsley (2015), Situation awareness misconceptions and misunderstandings [End15]

with the different enabling business processes being followed and with a divergent set of behaviour by the personnel engaged in the process. Further research is required to propose a model for the future DT, considering both generic and specific features with as minimum deviation within them as possible. Standards in the types of data needs and the design of a more precise but generic formulation of the KPIs are indispensable. During job shadowing, a work sampling approach was followed for identification in the first (dry) run, followed by quantification of deviations from the (documented) business process to analyse these findings further in this research setting. In principle, IoT can be employed to realise work sampling. Alternative models that statistically estimate and incorporate the process-related deviation need to be further investigated for the focus area of this study, namely, OR-WPS. Smart work sampling based on the Internet of Everything (IoE) may be applied for DT of the future without personal identification. These foundational elements can further create a ground for artificial decision making using machine learning or any similar approach.

7.5.5 Applying EA on Pilots

Concepts of EA management (EAM) were successfully employed in this study to align the objectives, mission, vision, goals of the research project with the final physical implementation by using information technology such as programming based on multi-agent methodology. TOGAF (the open group architecture framework) does not recommend its architecture management cycle for PoC. However, in this case, the intention was to demonstrate its utility in multi-agent simulation use cases and general applicability in research. Through this endeavour, it is expected that TOGAF will be increasingly used for use cases in the future, and its applicability in other areas may be reported.

7.6 Summary

In this study, a multi-agent simulation of the operating room workforce planning and scheduling process for decision support was conceptualised, implemented, tested, validated, and verified. Further, a simulation learning environment, also known as Lerncockpit, was developed using low-code programming. Even before the COVID-19 pandemic, the present workforce and new hires had used and learned about their work-related process flows using digital technologies. Nevertheless, healthcare still generally lags behind other sectors as regards the prevalence of digital technology. However, the trust and acceptance in digital technology and appropriate handling of personal data of the patients (and employees) themselves is a challenging topic, especially in Europe. Any future research should investigate virtual assistants, predictive analytics, and gamification techniques. It must be noted that digital technology can disrupt the learning and development (L&D) within the healthcare service discipline. Apart from the aforementioned proposals, which may or may not be investigated in other studies, interests in artificial intelligence and machine learning and its applications in areas such as patient monitoring, natural language processing, and data analytics are garnering research attention. The benefits and challenges associated with machine learning as well as the potential risk for patients and employees are currently being investigated. Therefore, it is recommended that an integrated approach be adopted to avoid failed research investments producing optimised societal benefits. The role of enterprise architecture in the digital transformation in the coming years will be a matter of prevalent interest.

In this study, the research questions were thoroughly addressed using suitable scientific methods. The findings of this study indicate that a value-based simulation of the business process is feasible and reasonable. The study provided an improved understanding of this area of research and identified a few unanswered questions, which can be potential research topics. Future exploration on the modified/improved digital twin operating room planning and scheduling process can reveal further knowledge regarding its acceptance in reality. Ongoing and new research conducted in this area could improve the lives of personnel engaged with healthcare service providers, indicating evident societal benefits of human well-being and positive impacts on the environment. However, the primary contribution of this study is to validate that the *multi-agent* models for modelling and simulation in the healthcare domain when not only classical but also value-based indicators are to be measured and used in decision-making procedures in an operating room planning and scheduling process. The error/noise due to business process, input data, and calculation of outputs need further validation via application in more areas of healthcare delivery or entirely different domains. During the ongoing COVID-19 pandemic in Germany and worldwide, it was reported that although the medical infrastructure was available (oxygen ventilators, patient beds and even Intensive Care Unit (ICU) beds), overall medical personnel was scarce. The personnel who could intubate, provide care to the patients, and skilfully check the medical instruments were unavailable. For a country such as Germany, which maintains the highest number of ICU beds per headcount globally, this is a setback. As a result of the experience during the ongoing COVID-19 pandemic, healthcare digitalisation has become a top agenda. Based on our current knowledge of existing and future technologies, a digital twin using artificial intelligence and simulation together with a human-in-loop paradigm could be remarkably promising. The focus should also be on a generic model with low data collection needs so as to offer an attractive value proposition for the policymakers and management of the healthcare providers.

A Appendix - Semi-SLR Results

No.	Title	Author	Year
1	Implementation of computer simulation projects in health care	Wilson	1981
2	Using simulation in out-patient queues: a case study	Fenghueih	1996
3	Modelling health care processes with SHARE	Boelle	1998
4	Health care management modelling	Vissers	1998
5	Using simulation to improve the decision-making process	Agatstei	1999
6	Developing shared understanding through simulation	Hardiker	1999
7	Animated simulation: A valuable decision support tool for practice improvement	Ledlow	1999
8	Simulation of a stroke unit careflow	Quaglini	2001
9	Resource reallocation in an emergency medical service system using computer simulation	Su	2002
10	HipMod: Development of a multi-agent audit-based computer simulation of hip fracture care	Currie	2003
11	Systematic review of the use and value of computer simulation modelling in population health and health care delivery	Fone	2003
12	An effective model for rapid skills acquisition through a simulation-based integrated learning environment	Boyd	2004
13	Business process and health care simulation	Damij	2004
14	Using computer simulation for surgical care process reengineering in hospitals	Kumar	2005
15	Simulation modelling in healthcare	Eldabi	2005
16	Using simulation to increase efficiency in blood supply chains	Jyrki	2006
17	A simulation study of scheduling clinic appointments in surgical care: individual surgeon versus pooled lists	Vasilakis	2006
18	The tide is turning: organizational structures to embed simulation in the fabric of healthcare	Gaba	2007
19	Simulation modelling in healthcare	Comas	2008
20	Simulation model for estimating the cancer care infrastructure required by the public health system	Gomes	2009

Table A.1: Part 1 - A list of the most relevant literature in the work context, using search keywords mentioned in the table before. Only the names of the first authors are provided.

No.	Title	Author	Year
21	The analysis of service station allocation in the hospital based on bottleneck model	Wu	2009
22	Discrete event simulation for performance modelling in health care: a review of the literature	Günal	2010
23	Applications of simulation within the healthcare context	Katsaliaki	2010
24	Improving decision making in healthcare services through the use of existing simulation modelling tools and new technologies	Katsaliaki	2010
25	Analysis of an open access scheduling system in outpatient clinics: A simulation study	Lee	2010
26	A systematic review of simulation studies investigating emergency department overcrowding	Paul	2010
27	Discrete-event simulation is dead, long live agent-based simulation!	Siebers	2010
28	Increasing utilization in a hospital operating department using simulation modeling	Steins	2010
29	Hospital registration process reengineering using simulation method	Su	2010
30	Simulation based analysis of patient arrival to health care systems and evaluation of an operations improvement scheme	Williams	2010
31	RFID-based clinical decision support system using simulation modeling	Al-Safadi	2011
32	Using simulation modeling to improve patient flow at an outpatient orthopedic clinic	Rohleder	2011
33	Principles of scarce medical resource allocation in natural disaster relief: a simulation approach	Cao	2012
34	Systems modeling and simulation applications for critical care medicine	Dong	2012
35	Modeling using discrete event simulation: A report of the ISPOR-SMDM modeling good research practices task force–4	Karnon	2012
36	Application of computer simulation modeling in the health care sector: a survey	Mielczarek	2012
37	SimLean: Utilising simulation in the implementation of lean in healthcare	Robinson	2012
38	A review on the relation between simulation and improvement in hospitals	van Lent	2012
39	Multi-criteria approach using simulation-based balanced scorecard for supporting decisions in health-care facilities: an emergency department case study	Abo-Hamad	2013
40	Simulation-based framework to improve patient experience in an emergency department	Abo-Hamad	2013

Table A.2: Part 2 - A list of the most relevant literature in the work context, using search keywords mentioned in the table before. Only the names of the first authors are provided.

No.	Title	Author	Year
41	Use of discrete event simulation to improve a mental health clinic	Kim	2013
42	A conceptual framework for hybrid system dynamics and discrete event simulation for healthcare	Chahal	2013
43	The regional healthcare ecosystem analyst (RHEA): A simulation modeling tool to assist infectious disease control in a health system	Lee	2013
44	A simulation study of appointment scheduling in outpatient clinics: Open access and overbooking	Lee	2013
45	Improvement in the operating room efficiency using Tabu search in simulation	Niu	2013
46	Admission and capacity planning for the implementation of one-stop-shop in skin cancer treatment using simulation-based optimization	Romero	2013
47	Using queuing theory and simulation model to optimize hospital pharmacy performance	Bahadori	2014
48	Improving the design and operation of an integrated emergency post via simulation	Borgman	2014
49	Uncovering effective process improvement strategies in an emergency department using discrete event simulation	Choon	2014
50	A flexible simulation platform to quantify and manage emergency department crowding	Hurwitz	2014
51	Planning intensive care unit design using computer simulation modeling: optimizing integration of clinical, operational, and architectural requirements	O´Hara	2014
52	A systematic literature review of agents applied in healthcare	Isern	2016
53	Combining modelling and simulation approaches	Bisogno	2016
54	Using the integration of discrete-event and agent-based simulation to enhance outpatient service quality in an orthopedic department	Kittipitt-ayakorn	2016
55	A design and engineering methodology for organization-based simulation model for operating room scheduling problems	Yahia	2017
56	A hybrid simulation approach to analyse patient boarding in emergency departments	Landa	2017
57	Application of simulation in healthcare service operations	Roy	2021
58	A simulation study on demand disruptions and limited resources for healthcare provision	Bowles	2021
59	Multi-agent system specification for distributed scheduling in home health care	Alves	2022

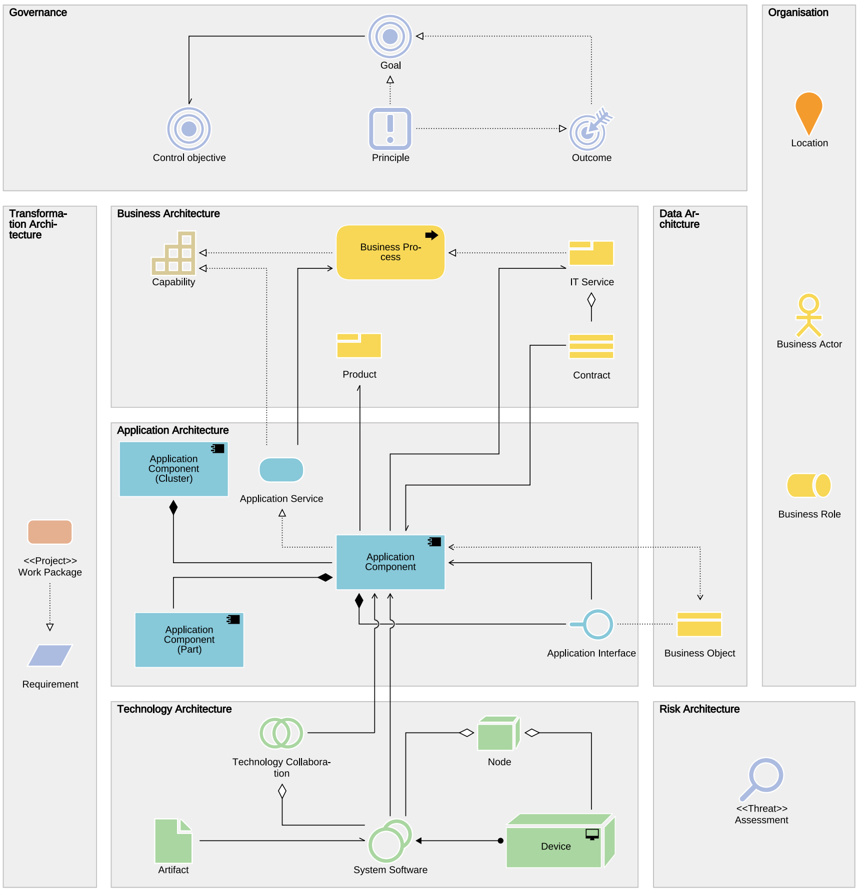
Table A.3: Part 3 - A list of the most relevant literature in the work context, using search keywords mentioned in the table before. Only the names of the first authors are provided.

Year	Example Title and Type of Contribution
2011	Reengineering aircraft structural life prediction using a digital twin (*journal*)
2012	The digital twin paradigm for future NASA and US Air Force vehicles; The airframe digital twin: some challenges to realization (in total 7 in Aeronautics and Manufacturing conferences); Clinical Biomechanics: Contributions to the Medical Treatment of Physical Abnormalities (in total 2 in healthcare journals)
2013	Recent advances and trends in predictive manufacturing systems in big data environment (in total 13 in Aeronautics and 2 in Manufacturing conferences); Recent advances and trends in predictive manufacturing systems in big data environment (in total 2 in journals)
2014	Multifidelity DDDAS methods with application to a self-aware aerospace vehicle (in total 15 in journals and conferences on Aeronautics, Manufacturing, Gaming et cetera);
2015	Do we need a national research agenda for modelling and simulation? (Winter Simulation Conference 2015) In total 25 in Aeronautics, Manufacturing conferences and journals;
2016	Digital Twin - The Simulation Aspect (more than 100 articles in journals and conferences)
2017	Integration of a digital twin as human representation in a scheduling procedure of a cyber-physical production system; Conceptual model of complex multi-agent system smart city 4.0 (and countless articles in several domains except healthcare)
2018	Pervasive Computing Integrated Discrete Event Simulation for a Hospital Digital Twin [Kar+01] (and numerous articles in journal and conference on correlation of hospital with DT; countless articles in Manufacturing and other related domains)
Q1 - 2019	Missed opportunities: two case studies of digitalisation of FM in hospitals (and countless articles in journals and conferences in Engineering, Marketing, Operations, Healthcare, Finance et cetera)

Table A.4: Semi-SLR of DT chronologically in different domains

B Appendix - Metamodel

A metamodel[1] is a model composed of model statements. The scope of the meta-model is based on the set of concerns of the modeller and the stakeholder. The model is described in terms of concepts and their relationship within the scope of the research project.



ArchiMate® metamodel used in this work based on modified model from the Adoit Community Edition (CE). The relationships among these elements follow ArchiMate® standards.

[1]Source: Manfred Jeusfeld (2009), Metamodel [Jeu09]

Literature

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Curriculum Vitae

Gaurang Phadke, born in 1979 in India, went to school at the Bishambhar Nath Sanatan Dharam (BNSD) Inter College in Kanpur, where he qualified for his intermediate exam. He studied mechanical engineering at the North Maharashtra University (NMU), Jalgaon and worked for four years at the Department of Atomic Energy, India. After getting the master's degree in business administration from Hochschule Stralsund (HOST) followed by in computer simulation from Rheinisch-Westfälische Technische Hochschule (RWTH), Aachen, in Germany; he started as a doctoral candidate at the Chair for Information Systems Management at the University of Bayreuth, Germany, with visiting scholar position at Department of Health Management and Informatics (HMI) at the University of Missouri, Columbia, USA.

Since 2016 he has been working at German-Dutch high voltage electricity grid operator TenneT at Bayreuth; at the beginning as an Information Manager, and presently as an Enterprise (IT) Architect; and in parallel as an external doctoral candidate for this research work at the University of Bayreuth. Gaurang Phadke is certified by Open Group in both ArchiMate® 3.0 and TOGAF® 9.2s' highest standards. He is also trained in the Data Management Body of Knowledge (DAMA DMBoK), IT4IT™ reference architecture and certified in Project In Controlled Environment (PRINCE2) by Axelos.

List of Publications

(a) **Phadke, Gaurang**; Walther, Sebastian; Ott, Matthias; Eymann, Torsten; Lerncockpit, Wertschöpfungsorientiertes Benchmarking; 249-278, 2015, Springer Heidelberg

(b) Walther, Sebastian; Eden, Rebekah; **Phadke, Gaurang**; Eichin, Rüdiger; Eymann, Torsten; The role of past experience with on-premise on the confirmation of the actual system quality of on-demand enterprise systems; Enterprise Systems, Strategic, Organizational, and Technological Dimensions; 198, 2015, Springer International Publishing

(c) Walther, Sebastian; Eymann, Torsten; Otto, Boris; Buck, Christoph; **Phadke, Gaurang**; The influence of prior on-premise use on the confirmation and perception of infrastructure-specific system quality; MKWI 2014, Multikonferenz Wirtschaftsinformatik; Paderborn, Germany

(d) **Phadke, Gaurang**; Buchholz, Sebastian; Volz, Bernhard; Walther, Sebastian; Niemann, Christoph; Eymann, Torsten; An agent-based simulation tool for the evaluation of surgical-operation schedules, European Social Simulation Association 2013 Conference; Salzburg, Austria

(e) Walther, Sebastian; Plank, Andreas; Eymann, Torsten; Singh, Niraj; **Phadke, Gaurang**; Success Factors and Value Propositions of Software as a Service Providers – A Literature Review and Classification, AMCIS 2012 Proceedings; Seattle, United States of America

(f) Walther, Sebastian; **Phadke, Gaurang**; Eymann, Torsten; ,The service-productivity learning cockpit – a business intelligence tool for service enterprises, Bayreuther Arbeitspapiere zur Wirtschaftsinformatik, 53, 2012; Bayreuth, Germany