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(UFRGS)
Escola de Engenharia (EE)
Programa de Pós-Graduação em
Engenharia Civil: Construção e Infraestrutura
(PPGCI)

Macquarie University
(MQ)
Australian Institute of Health Innovation (AIHI)
Faculty of Medicine, Health and Human Sciences
(FMHHS)

Natália Ransolin

A framework of built environment design knowledge supportive of resilient internal logistics in hospitals

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NATÁLIA RANSOLIN

A framework of built environment design knowledge supportive of resilient internal logistics in hospitals

This thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy (Ph.D.)

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Universidade Federal do Rio Grande do Sul (UFRGS)

Macquarie University (MQ)

Supervised by

Prof. Tarcisio Abreu Saurin
Ph.D. (UFRGS, Brazil)
Supervisor, UFRGS

Prof. Robyn Clay-Williams
Ph.D. (UNSW, Australia)
Supervisor, MQ

Prof. Carlos Torres Formoso
Ph.D. (University of Salford, UK)
Co-supervisor, UFRGS

Prof. Frances Rapport
Ph.D. (Staffordshire University, UK)
Co-supervisor, MQ

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NATÁLIA RANSOLIN

A framework of built environment design knowledge supportive of resilient internal logistics in hospitals

This Doctoral Thesis was judged as part of requirements for obtaining the title of DOCTOR IN CIVIL ENGINEERING, research area Management and Economics of Construction, and approved in its final form by the Supervisor Professors and the Postgraduate Program in Civil Engineering: Construction and Infrastructure at the Universidade Federal do Rio Grande do Sul.

Porto Alegre, 8th of March, 2024.

Prof. Tarcisio Abreu Saurin
Ph.D. (UFRGS, Brazil)
Supervisor, UFRGS

Prof. Robyn Clay-Williams
Ph.D. (UNSW, Australia)
Supervisor, MQ

Prof. Carlos Torres Formoso
Ph.D. (University of Salford, UK)
Co-supervisor, UFRGS

Prof. Frances Rapport
Ph.D. (Staffordshire University, UK)
Co-supervisor, MQ

Prof. Ana Carolina Badalotti Passuello
Coordinator PPGCI/UFRGS

EXAMINERS

Prof. Daniela Dietz Viana (UFRGS)
Ph.D. (UFRGS, Brazil)

Prof. Alessandro Jatobá (Fiocruz)
Ph.D. (UFRJ, Brazil)

Prof. Zofia K. Rybkowski (Texas A&M University)
Ph.D. (University of California-Berkeley, U.S)

NATÁLIA RANSOLIN

A FRAMEWORK OF BUILT ENVIRONMENT DESIGN KNOWLEDGE SUPPORTIVE OF RESILIENT INTERNAL LOGISTICS IN HOSPITALS

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Sydney, 8th of March, 2024.

Prof. Tarcisio Abreu Saurin
Ph.D. (UFRGS, Brazil)
Supervisor, UFRGS

Prof. Robyn Clay-Williams
Ph.D. (UNSW, Australia)
Supervisor, MQ

Prof. Carlos Torres Formoso
Ph.D. (University of Salford, UK)
Co-supervisor, UFRGS

Prof. Frances Rapport
Ph.D. (Staffordshire University, UK)
Co-supervisor

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“Gracias a la vida que me ha dado tanto”
(*Violeta Parra*)

STATEMENT OF ORIGINALITY

This thesis is being submitted to Macquarie University and Federal University of Rio Grande do Sul (UFRGS) in accordance with a Cotutelle agreement between both institutions dated 21/07/2021. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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Natália Ransolin

Sydney, 08/03/2024

ABSTRACT

RANSOLIN, N. **A framework of built environment design knowledge supportive of resilient internal logistics in hospitals**. 2024. Thesis (Ph.D. in Civil Engineering) - Postgraduate Program in Civil Engineering: Construction and Infrastructure, Engineering School, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2024. In cotutelle with Australian Institute of Health Innovation, Faculty of Medicine, Health and Human Sciences, Macquarie University, Sydney, 2024.

The built environment (BE) influences the performance of health services, including patient outcomes, through a number of factors such as wayfinding, layout, and the flexibility of room configurations. These factors have been investigated mostly in the context of the evidence-based-design (EBD) literature. Although EBD literature is vast, its contribution to resilient performance (RP) - i.e., the systems property of coping with both expected and unexpected variabilities, maintaining the core system functionalities even under stress - has not been made explicit. Thus, the implications of this literature for the RP of specific hospital units and processes have not been explored. The aim of this research work is to develop a framework of BE design knowledge supportive of RP in the internal logistics of hospitals, a crucial process that spans large physical areas and involves activities of storage and transportation of patient and supplies. The framework is composed of different levels of abstraction ranging from principles relevant to any hospital unit to context-specific practical examples. Initially, a systematic literature review was carried out to develop generic BE design knowledge supportive of RP, based on concepts from resilience engineering and complex socio-technical systems. This knowledge is composed of meta-principles, principles, prescriptions, and practical examples of the influence of the BE on the RP across a broad set of health services. Next, this knowledge was refined based on two case studies, which also allowed for tailoring it to internal hospital logistics. The case studies were set in two teaching hospitals, focusing on activities of internal logistics that occurred in: (i) the common areas linking an intensive care unit (ICU) to other units of a large public hospital in Brazil; and (ii) the surgical service of a private hospital in Australia. Both case studies were based on multiple sources of evidence, including interviews with 48 healthcare professionals, 94 hours of non-participant observations, and consultation of a wide variety of documents, predominantly regulations. Findings from the first case study gave rise to seven prescriptions and 63 examples of the influence of the BE on the RP in the internal logistics to and from ICUs. In the second case study, those same seven prescriptions served as data analysis themes that allowed the identification of 60 examples relevant to internal logistics in surgical services. Results from both case studies also shed light on the importance of understanding the service flows within hospitals, as they highlight what happens intra and inter workspaces, providing a systems perspective for the BE design. Synthesising all data collected along the research process, a general framework of BE design knowledge supportive of RP in internal hospital logistics was derived. The framework is composed of four meta-principles, seven principles, seven prescriptions, and 181 practical examples. The results of this study are new in the context of health services, offering guidance to both BE and operations designers.

Keywords: Built environment. Healthcare. Resilience. Internal hospital logistics. Intensive care units. Surgical services.

RESUMO

RANSOLIN, N. **Estrutura de conhecimento de projeto de ambiente construído de apoio à logística interna resiliente em hospitais**. 2024. Tese (Doutorado em Engenharia Civil) - Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura, Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2024. Em cotutela com Australian Institute of Health Innovation, Faculty of Medicine, Health and Human Sciences, Macquarie University, Sydney, 2024.

O ambiente construído (BE) influencia o desempenho dos serviços de saúde, incluindo os resultados dos pacientes, através de uma série de fatores, como orientação, layout e flexibilidade das configurações dos quartos. Esses fatores foram investigados principalmente no contexto da literatura de design baseado em evidências (EBD). Embora a literatura sobre EBD seja vasta, a sua contribuição para o desempenho resiliente (RP) - ou seja, a propriedade dos sistemas de lidar com variabilidades esperadas e inesperadas, mantendo as funcionalidades centrais do sistema mesmo sob estresse - não foi explicitada. Assim, as implicações desta literatura para o RP de unidades e processos hospitalares específicos não foram exploradas. O objetivo deste trabalho de pesquisa é desenvolver uma estrutura de conhecimento de design de BE que apoie a RP na logística interna de hospitais, processo que ocorre em diversas áreas e envolve o armazenamento e transporte de pacientes e suprimentos. A estrutura é composta por diferentes níveis de abstração, desde princípios relevantes para qualquer unidade hospitalar até exemplos práticos específicos do contexto. Inicialmente, foi realizada uma revisão sistemática da literatura para desenvolver conhecimentos genéricos de design de BE que apoiassem a RP, com base em conceitos de engenharia de resiliência e sistemas sociotécnicos complexos. Esse conhecimento é composto por metaprincípios, princípios, prescrições e exemplos práticos da influência do BE na PR em um amplo conjunto de serviços de saúde. Em seguida, esse conhecimento foi refinado com base em dois estudos de caso, o que também permitiu adequá-lo à logística interna hospitalar. Os estudos de caso foram realizados em dois hospitais universitários, com foco em atividades de logística interna ocorridas: (i) nas áreas comuns que ligam uma unidade de terapia intensiva (UTI) a outras unidades de um hospital público de grande porte no Brasil; e (ii) no serviço cirúrgico de um hospital privado na Austrália. Ambos os estudos de caso se basearam em múltiplas fontes de evidência, incluindo entrevistas com 48 profissionais de saúde, 94 horas de observações não participantes e consulta de uma ampla variedade de documentos, predominantemente regulamentos. Os resultados do primeiro estudo de caso deram origem a sete prescrições e 63 exemplos da influência do BE sobre a PR na logística entre UTIs. No segundo estudo de caso, essas mesmas sete prescrições serviram como temas para análise de dados que permitiu a identificação de 60 exemplos relevantes para a logística interna em serviços cirúrgicos. Os resultados de ambos os estudos de caso também esclarecem a importância de compreender os fluxos de serviço dentro dos hospitais, pois destacam o que acontece intra e interespaços de trabalho, fornecendo uma perspectiva sistêmica para o design de BE. Sintetizando todos os dados coletados ao longo do processo de pesquisa, foi derivada uma estrutura geral de conhecimento de design de BE que apoia a PR na logística interna do hospital. A estrutura é composta por quatro metaprincípios, sete princípios, sete prescrições e 181 exemplos práticos. Os resultados deste estudo são novos no contexto dos serviços de saúde, oferecendo orientação tanto para projetistas de BE quanto de operações.

Palavras-chave: Ambiente Construído. Serviços de saúde. Resiliência. Logística hospitalar. Serviços cirúrgicos.

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LIST OF ACRONYMS

AIHI: Australian Institute of Health Innovation

BE: Built Environment

BEAD: Built Environment-as-Done

BEAI: Built Environment-as-Imagined

BIM: Building Information Modelling

c-ICU: ICU connecting areas

CSSs: Complex Socio-Technical Systems

DfRP: Design for Resilient Performance

EBD: Evidence-based Design

EBM: Evidence-based Medicine

EE: Escola de Engenharia

FMHHS: Faculty of Medicine, Health and Human Sciences

FRAM: Functional Resonance Analysis Method

ICU: Intensive Care Unit

MQ: Macquarie University

NSW: New South Wales

OR: Operating Room

PACU: Postanaesthesia Care Unit

PPGCI: Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura (Postgraduate Program in Civil Engineering: Construction and Infrastructure)

RP: Resilient Peformance

UFRGS: Universidade Federal do Rio Grande do Sul (Federal University of Rio Grande do Sul)

WAD: Work-as-Done

WAI: Work-as-Imagined

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1 INTRODUCTION

1.1 CONTEXT

The growing demand for health services and specialized care is a global trend, partly resulting from ageing populations with chronic diseases (McArthur et al., 2021). The higher life expectancy increases the number of people presenting long-term health conditions – i.e., comorbidity – which challenges services to maintain care delivery levels (Tsekleves and Cooper, 2017). In order to care for patients in an increasingly complex external environment, health services themselves have become more complex, being widely recognized as Complex-Socio Technical Systems (CSSs) (Braithwaite et al., 2013). These systems are characterized by a large number of diverse and dynamically interacting human, technical, and organizational elements, all subjected to the influence of the external environment (Braithwaite, 2018). This thesis considers the interactions between those elements in healthcare, emphasizing how several types of processes, technologies and stakeholders (e.g., providers, caregivers, patients, and families) interact with the built environment (BE) in the provision of care. The BE is a technical system comprised of a man-made building that supports a particular type of activity (Hollnagel, 2014a; Hassler and Kohler, 2014). This work adopts an extended definition of BE that encompasses the building, furniture, fixtures, equipment, and visual signs. The BE relevance for the performance of health services has been acknowledged by several studies, which have pointed out that it has a tangible influence on both patient outcomes and caregivers´ performance (Hicks et al., 2015; Real et al., 2017; Machry et al., 2021).

A substantial portion of the body of knowledge on the BE influence on health services has been produced in the field of Evidence-Based Design (EBD). Some studies on that topic aim to support designers and managers by providing evidence of the BE influence on patient outcomes and the performance of health services (Ulrich et al., 2008; Lu and Price, 2011). The concept of EBD is similar to that of Evidence-based Medicine (EBM), which aims to provide evidence to support clinical decision-making. In the 1980s, the spread of EBM led to adaptations of that approach to the context of the design of healthcare facilities, giving rise to the field of EBD (Ulrich, 1984; Zhang et al., 2016). EBD has produced evidence of BE impacts on healthcare stemming from noise, light, privacy, comfort, views of gardens and sunlight, access to the external environment, and accessibility, among others (Rybkowski, 2009; Zhang et al., 2019). These impacts are mostly related to the efficiency and safety of providing care. For instance, different layout configurations of nursing stations have different efficiency and safety implications (Colman et al., 2020; Greer et al., 2021).

The COVID-19 pandemic highlighted the challenges for health services in coping with uncertainties, and the need for health systems to be resilient (Carayon and Perry, 2021), yet the potential contribution of BE has not been established. This thesis explores the BE contribution to the resilient performance (RP) of health services. RP is investigated from the perspective of resilience engineering (Hollnagel et al., 2013), which focuses on analysing how systems adjust their performance to cope with both expected and unexpected conditions, while continuing to produce required outputs (Hollnagel, 2017). From the viewpoint of resilience engineering, RP is an emergent phenomenon that arises from the interactions between the system elements; although these interactions might be deliberately influenced by design, they cannot be completely controlled and anticipated (Wachs et al., 2016). RP should be supported across all levels of health services, namely: macro (e.g., national healthcare system), meso (e.g., hospital internal logistics), and micro levels (e.g., hospital units) (Berg et al., 2018). However, understanding the interactions between these levels has been an under-explored topic (Ellis et al., 2019). The application of resilience engineering to health services gave rise to the notion of resilient healthcare, which is *"the ability of the healthcare system (a clinic, a ward, a hospital, a county) to adjust its functioning prior to, during, or following events (changes, disturbances or opportunities), and thereby sustain required operations under both expected and unexpected conditions"* (Hollnagel et al., 2013).

RP in hospital operations can be achieved with the management of the inherent variability of CSSs, through the planning and coordination of the system elements – e.g., related processes, resources, and technologies (Braithwaite, 2018; Jolgehnejad et al., 2021). A typical variability present in hospitals is patient deterioration, an expected condition that requires a rapid response and can be supported by layouts with direct access from nursing stations to patient bays (Pouyan et al., 2021). In turn, to minimise interruptions of daily operations during unexpected conditions such as infectious diseases, the BE design might promote the independence of hospital units, allowing the separation of functional areas without major work disruptions (Capolongo et al., 2020). Resilient healthcare, like resilience engineering, is concerned with RP during both everyday work and during chronic and acute crises such as pandemics, and natural or man-made disasters. However, the notion of everyday variability is the most distinctive characteristic of resilient engineering and resilient healthcare, and is based on the observation that RP usually remains unexplored due to the successful outcomes that are obtained most of the time (Bueno et al., 2021).

Everyday work with normal operational conditions also involves unwanted variabilities (e.g., scarcity of resources, efficiency pressures) that might be concealed due to successful RP (Hollnagel, 2014b). Thus, resilience engineering gives visibility to RP that otherwise may be taken for granted by managers, who can assume that successful outcomes are obtained only as a result of closely following procedures and full compliance with rules and policies driven top-down (Hollnagel, 2014b). Kamara et al. (2020) expand on this point arguing that resilience relies on how the BE is adapted by its users on a daily basis. The resilience engineering focus on everyday work is worth emphasizing as there is a significant body of literature (Achour and Price, 2010; Capolongo et al., 2020; Keenan, 2020; Ochi et al., 2020; Ransolin et al., 2021) related to BE resilience to cope with natural and man-made disasters. Although relevant, RP under these conditions is out of the scope of this thesis.

1.2 RESEARCH PROBLEM

Although EBD is a source of knowledge for designers, it does not provide a standard for repetition and testing but rather a process that continuously produces "ad hoc" solutions (Codinhoto, 2013; Alfonsi et al., 2014). Thus, evidence is bounded to a specific context which, given the very large number of possible contexts, contributes to the fragmentation of EBD knowledge and hinders its implementation in real-world settings (Codinhoto et al., 2010; Zhang et al., 2016).

Moreover, EBD is commonly criticized for not accounting for the complexity of health services, overlooking the variability of the activities that occur in the BE, and the consequent need for RP to facilitate safe delivery of care (Becker et al., 2011; Zhang et al., 2016; Halawa et al., 2020; Łukasik and Porębska, 2022). From the perspective of resilience engineering, this EBD drawback is a failure to acknowledge the gap between work-as-imagined (WAI) in design and procedures and work-as-done (WAD) in reality (Ransolin et al., 2020; Machry et al., 2021; Joseph et al., 2022). Although previous EBD research studies have investigated some facets of resilience, such as flexibility and adaptability, contributions to resilient healthcare have not been made explicit and jointly articulated (Pati et al., 2008; Aalto et al., 2019; France et al., 2009). Further, most studies linking BE and resilience are usually technical oriented, e.g., oversizing of load-bearing structures as a BE resilient characteristic (Brambilla et al., 2021). Despite this, the multidisciplinary character of EBD literature, in which knowledge arises from psychology, architecture, sociology, anthropology, marketing, engineering, human factors and ergonomics, and human behaviour research (Rybkowski, 2009), suggests that it may be compatible with the socio-technical and systemic perspective of resilience engineering.

As a possibility for addressing the aforementioned fragmentation of EBD contributions, the corresponding knowledge base might be structured according to different levels of abstraction, from high-level design guidance that is fairly generalizable, to low-level practical solutions that are highly context-dependent. In fact, similar ideas have been proposed in the EBD literature, albeit not addressing RP. For example, Zhang et al. (2019) developed a framework to understand the effects of healing BE characteristics on patients' health outcomes and well-being. The framework was devised according to design principles (e.g., 'comfortable environment'), followed by design parameters (e.g., 'light'), which gave rise to sub-parameters (e.g., 'daylight').

A similar hierarchical approach for the structuring of design knowledge is implicit in the use of requirements management, which provides a language and methods to identify, prioritize, control, and disseminate solutions to fulfil BE requirements at different levels of abstraction (Kamara et al., 2002). High abstraction levels are closely related to clients' perceived values, represented in hierarchical value maps (Lee and Lin, 2011; Kumar et al., 2020). However, requirements management is usually adopted as a practical approach in specific projects rather than for producing generalizable knowledge at the industry level. For instance, Baldauf et al. (2021) evaluated an emergency department, focusing on requirements captured from users, regulations, and processes.

Therefore, there is a lack of hierarchically organized EBD knowledge for the design of BE supportive of RP. From perspective of resilience engineering, RP is a functional and dynamic property of socio-technical systems (Hollangel, 2014b). This implies that any investigation of the links between RP and BE needs to consider how people dynamically interact with BE, rather than only considering it from a static and technical perspective.

This thesis addresses this gap by proposing a design knowledge framework, based on both a systematic literature review and two case studies focused on BE support to the internal logistics of hospitals. Logistics encompasses the handling, transportation, and storage of human and technical assets, often spanning large physical areas (Volland et al., 2017; Jawab et al., 2018). These activities should fulfil patient care requirements at the right time and place (Moons et al., 2019).

Internal hospital logistics is constrained by the BE, which influences, for example, the choice of routes and transportation equipment, walking distances, and elevator use (Cubukcuoglu et al., 2021). However, literature on hospital logistics has not made explicit the role of the BE (Prugsiganont and Jensen, 2019; Machry et al., 2022). The consequences of poorly designed interconnecting areas can impact the quality of care transition between hospital units, which should be as smooth as possible, especially for critical patients – e.g., bumps on the floor may disconnect life support equipment from the patient stretcher (Rosso & Saurin, 2018; Copeland and Chambers, 2017; Ransolin et al., 2020). Similarly, other factors that might hinder the RP in hospital internal logistics are the lack of resources availability, limited autonomy, and fragmentation of supply providers (Ravaghi et al., 2022).

Two contexts for the study of internal hospital logistics are addressed in this thesis. The first case study is concerned with internal logistics in the common areas that involve service flows to and from intensive care units (ICU). The relevance of these areas are related, for instance, to the use of waiting areas for patients before exams, and to the transportation of critically-ill patients (Copeland and Chambers, 2017). The second case study investigates logistics activities in a surgical service that requires the articulation of several human and technological resources, under conditions of uncertainty, time, safety, and cost pressures (Braithwaite et al., 2017; Göras et al., 2019). BE plays an important role in surgical services as these need to be flexible to cope with a wide variety of clinical procedures, while facilitating short set ups of operating rooms (ORs) (Skaugset et al., 2016; Göras et al., 2019). Setting up ORs illustrates the relevance of investigating workflows that occur in support areas, as supplies and staff must be synchronised for surgery to occur (Ahmadi et al., 2019; Göras et al., 2019). This study advances knowledge in relation to prior studies that focused on the BE of ORs (Neyens et al., 2019; Taaffe et al., 2023) by considering the BE of the whole surgical service in the investigation of RP. Both case studies are underpinned by a systematic literature review of BE supportive of RP, although not specific to the internal logistics context.

Considering jointly the two case studies, attention is paid to the relationships between the BE and logistics flows intra and inter hospital units, thus adopting a systems perspective. The proposed design knowledge framework is organized according to different levels of abstraction (i.e., design meta-principles, design principles, design prescriptions, and practical examples), addressing the role of BE to support RP during everyday work.

1.3 RESEARCH QUESTIONS

The main research question of this investigation was: **How can we develop built environment design knowledge supportive of resilient internal logistics in hospitals?**

The main research question was broken down into three secondary questions that correspond to the research papers that make up this thesis, as follows:

1. How can we design a built environment supportive of resilient performance during everyday work in health services?
2. How can we develop built environment design knowledge that supports resilient performance in the internal logistics to and from ICUs in hospitals?
3. How can we develop built environment design knowledge that supports resilient performance in the internal logistics and perioperative areas of surgical services?

1.4 RESEARCH OBJECTIVES

The main objective of this research study was **to propose a framework of built environment design knowledge supportive of resilient internal logistics in hospitals.**

The secondary objectives of this research are to:

1. Develop built environment design knowledge to support resilient healthcare by systematically reviewing the evidence-based design literature;
2. Develop built environment design knowledge supportive of resilient internal logistics to and from ICUs in hospitals;
3. Develop built environment design knowledge supportive of resilient internal logistics and perioperative areas of surgical services.

1.5 THESIS STRUCTURE

This thesis is composed of six chapters: introduction; research method overview, three chapters corresponding to papers that address the secondary objectives; and the last chapter providing the discussion and conclusion, which articulates all findings and shows how the main objective has been addressed. Table 1 below summarizes the main content of each thesis chapter.

Chapters	Main content
1 – Introduction	• Context; • Research Problem; • Research Questions; • Research objectives; • Thesis Delimitation; • Thesis Structure
2 – Research Method Overview	• Research Strategy • Research Design
3 – Paper 1	• Systematic Literature Review (Ransolin et al., 2022)
4 – Paper 2	• Manuscript of the first case study (Ransolin et al., 2024a)
5 – Paper 3	• Manuscript of the second case study (Ransolin et al., 2024b)
6 – Discussions and Conclusion	• Thesis Closure

Table 1- Thesis Structure.

2 RESEARCH METHOD OVERVIEW

This chapter presents an overview of the research method, including the research strategy and research design.

2.1 RESEARCH STRATEGY

Case study was the research strategy adopted in this thesis. According to Yin (1994), it is a proper research strategy when "how" questions are proposed, providing rich contextual data and enabling a deep understanding of the phenomenon under investigation – i.e., in this thesis, how BE supports RP in the internal logistics in hospitals. Furthermore, case studies allow for developing both generalizable and context-specific knowledge (Yin, 2017), which is consonant with the objective of developing BE design knowledge across different levels of abstraction.

The selection of relevant cases is crucial for establishing external validity. Thus, the two selected hospital workflows and areas (i.e., flows of people and supplies in the connecting areas of an ICU and in a surgical service) were assumed to be highly complex, involving a wide variety of interacting processes displaying the characteristics of RP to a significant extent. Internal validity was achieved by following good practices of case-based research, namely: development of data collection protocols (Eisenhardt and Graebner, 2007); triangulation of data and data sources (Noor, 2008); development of a database, allowing traceability and reinterpretation of data when necessary (Flybjerg, 2011); use of visual representations to illustrate the contributions of the study (Eisenhardt and Graebner, 2007); and presentation of the results to the participants of the case studies, to obtain their feedback (Rapport et al., 2018). Hospital representatives who participated in the case studies were professionals with expertise, experience, or practical knowledge, providing valuable information.

In both case studies, data collection followed a qualitative orientation, which was useful for understanding a broad range of situations in which the BE influences RP. In fact, there has been a growing recognition of the utility of qualitative methods to uncover complex processes and provide new research perspectives of health services (Tong et al., 2007; Rapport and Braithwaite, 2020). These methods shed light on EBD in context, exploring the strengths and weaknesses of BE design knowledge in the face of different technological, social, and organizational environments (Pati et al., 2011; Codinhoto, 2013; Rapport et al., 2020).

This thesis started with a systematic literature review to investigate the BE contributions to RP and then following with case studies as a basis for generating design knowledge in different levels of abstraction, for the design of BE supportive of RP. For this purpose, sources of evidence used in the case studies were based on documents (e.g., regulations, drawings, and photos), semi-structured interviews, participant and non-participant observations (e.g., meetings, walkthrough sessions, and focus groups). Based on the joint analysis of the findings from the systematic literature review and the case studies, emerging patterns were identified and gave rise to a design knowledge framework that answers the main research question. As such, each of the three major research activities (i.e., one systematic literature review and two case studies) successively refined the design knowledge.

Case-based research has consistently been a powerful method of knowledge production in management in general (Voss et al., 2002; Meredith, 1998). The elements of the design knowledge framework derived in this thesis might be interpreted as propositions for theory testing in future studies in other hospital settings. In contexts that are equivalent to that explored in this thesis, the design knowledge might be applied proactively to the design or re-design of healthcare facilities. The expectation is that the uptake of the design knowledge will contribute to improved RP of health services.

2.2 RESEARCH DESIGN

This thesis is supported by the Doutorado Acadêmico para Inovação (Academic Doctorate for Innovation), funded by the Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq (National Council for Scientific and Technological Development)/ Brazil, and carried out at Federal University of Rio Grande do Sul (UFRGS) in collaboration with industry. Thus, this thesis was partially held in partnership with a large public teaching hospital, a reference in highly complex treatments in Southern Brazil. The first case study was carried out in that hospital. Several studies from the same research group (i.e., Bueno et al., 2021; Bertoni et al., 2021; Gayer et al., 2020; Ransolin et al., 2020, and others under development) have been part of a research project named "Development of New Methods for Operations Management in Health Services". The research work carried out in the first case study was analysed and approved by the hospital ethical committee (CAEE number 79424617.0.0000.5327 – Appendix A).

Furthermore, this thesis is carried out under a cotutelle program involving UFRGS and Macquarie University (MQ), in Sydney, Australia. This program requires the Ph.D. student to spend 12 months at the partner institution and 12 months conducting research locally at MQ, which corresponded to the period for developing the second case study. The same thesis must be submitted simultaneously at UFRGS and MQ. The MQ onsite component was funded by an International Macquarie University Research Excellence Scholarship (iMQRES) Scheme.

The institution selected for the development of the second case study is a medium-sized private teaching hospital servicing a high socio-economic population in metropolitan New South Wales (NSW), Australia. Recent research with similar interest of investigating the role of the BE on daily work was conducted in the OR environment of the same surgical service (Rapport et al., 2020). The research project met the requirements set out in the National Statement on Ethical Conduct in Human Research 2007 (Reference No: 520221248843909 – Appendix B).

Regarding the research design, Figure 1 outlines the three stages of this investigation, each one divided into specific research activities as suggested by Yin (1994), to address the research questions and objectives. Initially, the thesis had an exploratory character, aimed at understanding the research problem and building the theoretical foundations for further investigation (Hair et al., 2019).

Stage I ("Define and Design") consisted of a systematic literature review with the aim of producing design knowledge, including meta-principles, principles, prescriptions, and practical examples (paper 1). Then, in Stage II, namely "Prepare, Collect, and Analyse", two case studies were carried out with the aim of refining the design knowledge framework (papers 2 and 3, respectively). Paper 2 gave rise to seven design prescriptions, hence being used as themes for data analysis of the study case of paper 3. The corresponding research activities included selecting the case studies, designing data collections protocols, conducting case studies, and reporting the results for each study. The hospital where the research project is approved in Brazil was chosen to conduct case study 1 - i.e., paper 2 of this thesis. Macquarie University Hospital was chosen for the activities carried out in case study 2 for paper 3. Further detail on the research settings is provided in the relevant chapters. Finally, **stage III**, titled "analyse and conclude", was undertaken to connect the findings from the three papers, resulting in the thesis conclusions.

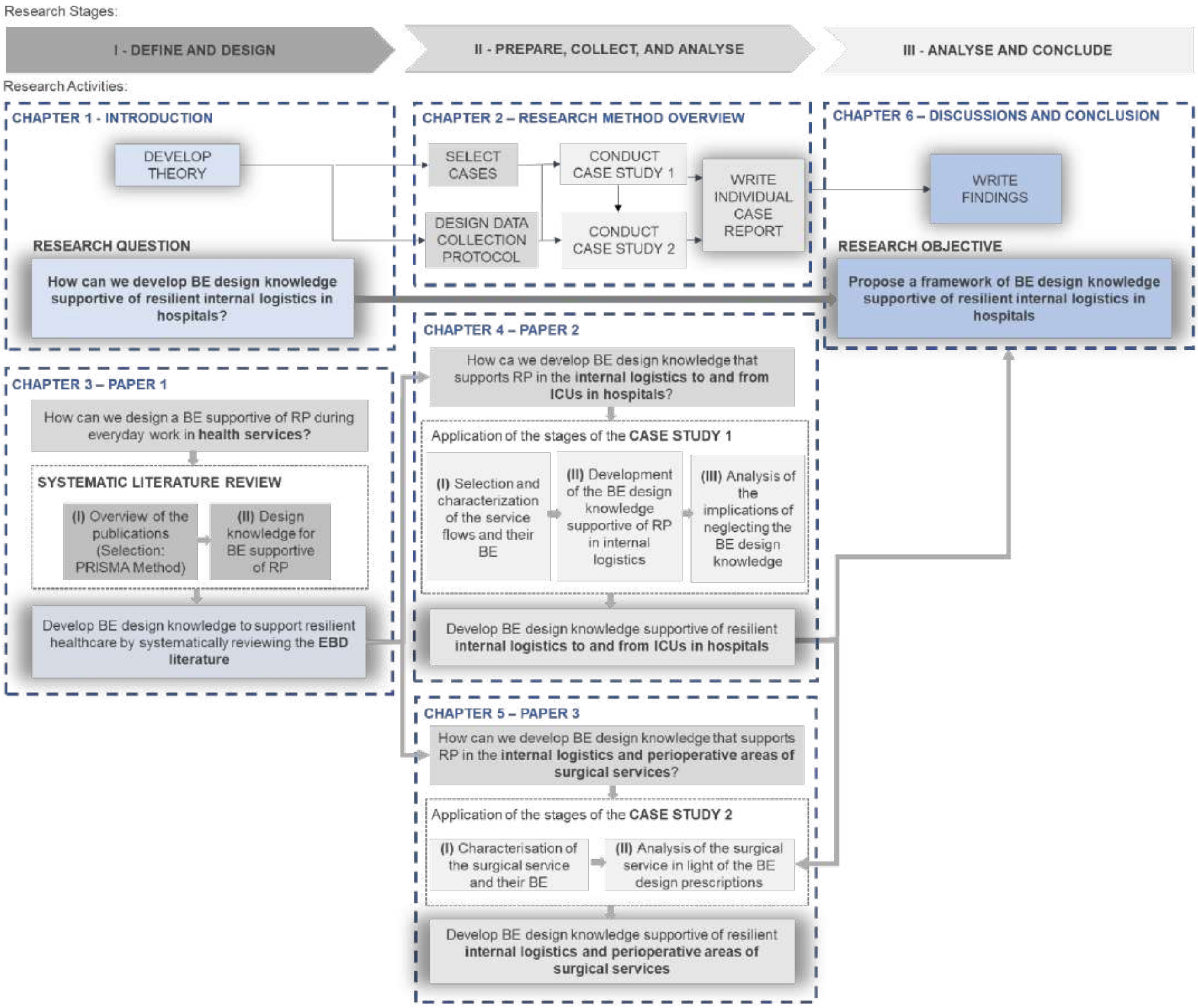

Figure 1 – Thesis research design and thesis chapters.

Table 2 depicts the total hours of data collection in each case study of the thesis. More than 130 hours were dedicated to gathering evidence from documents, observations, interviews, and meetings. The difference of 30 hours between the studies can be partially explained by the nature of the settings investigated. While in paper 2 the focus was on the areas that involved common areas in the inter hospital units of a large public hospital (81 hours), paper 3 paid attention to the intra unit areas of a medium-sized private hospital (52 hours).

Data collection	**Sources of evidence**				
	Document analysis	**Non-participant observations**	**Semi-structured interviews**	**Meetings with hospital staff**	Total (hours)
Paper 2 – internal hospital logistics/ ICU connecting areas	**-**	**50**	**30**	**1**	**81**
Paper 3 – surgical service		30	16	6	**52**
					133

Table 2 – Total of data collection (hours) of case studies associated with the sources of evidence.

The research objectives of this thesis were achieved by three scientific papers, each of them addressing a respective research objective, as abovementioned. Table 3 shows the association of the research objectives with the paper titles, the scientific journal they are published/submitted, and their Journal Impact Factors (JIF).

Research Objectives	Paper Title	Scientific Journal	Status	JIF - 5 year
1	The Built Environment influence on Resilient Healthcare: A Systematic Literature Review of Design Knowledge	Health Environments Research & Design Journal (HERD)	Published	2.4
2	Built Environment Design Knowledge Supportive of Resilient Performance in Hospital Internal Logistics	Applied Ergonomics (AE)	Under revision (1st)	3.2
3	Beyond the Operating Room: Built Environment Design Knowledge Supportive of Resilient Surgical Services	*Engineering,* Construction and Architectural Management (ECAM)	Submitted	4.1

Table 3 – Thesis research papers and publication status.

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3 PAPER I – Systematic Literature Review

This chapter presents the first paper of the thesis, which is a systematic literature review to investigate to which extent the EBD accounts for the role of the BE for RP in health services. The main outcome of this paper is general design knowledge to be used in various contexts rather than in a specific health setting.

The paper was published in HERD: Health Environments Research & Design Journal. Findings were also presented at two international conferences hosted online (citations below). The journal text has been formatted to fit these pages.

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Supplementary Material - Appendix C

Authorship statement - Appendix D

Presentations - Appendix H:

N. Ransolin, C. M. Zani, T. A. Saurin, C. T. Formoso, Rapport, F. (2021). Does Evidence-based Design Fit the Complexity of Healthcare Services?. In: *Resilient Health Care Society Virtual Summer Meeting*. 2021, Jönköping.

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The Built Environment Influence on Resilient Healthcare: A Systematic Literature Review

Natália Ransolin, Tarcisio Abreu Saurin, Caroline Melecardi Zani, Frances Rapport; Carlos Torres Formoso, Robyn Clay-Williams

Abstract

Objective: The aim of this study was to develop built environment (BE) design knowledge to support resilient healthcare by systematically reviewing the evidence-based design (EBD) literature. **Background**: Although the EBD literature is vast, it has not made explicit its contribution to resilient healthcare, which is a key component of the highly complex health service. **Method**: This review followed the steps recommended by the Preferred Reporting Items for Systematic reviews and Meta-Analyses method. After applying the inclusion and exclusion criteria, 43 journal papers were selected. The papers were analyzed in light of five guidelines for coping with complexity, allowing for the development of BE design knowledge that supports resilient healthcare. **Results**: The design knowledge compiled by the review was structured according to four levels of abstraction: design meta-principles, corresponding to the five complexity guidelines, seven design principles, 21 design prescriptions, and 58 practical examples. The design knowledge emphasizes the interactions between the BE as physical infrastructure and the functions that it supports. **Conclusions**: The design knowledge is expected to be useful not only to architects but also to those involved in the functional design of health services as they interact with the BE. Furthermore, our proposal provides a knowledge template that can be continuously updated based on the experience of practitioners and academic research.

Keywords: health services, evidence-based-design, resilience, complexity, built environment.

3.1 INTRODUCTION

The influence of the built environment (BE) on the performance of health services has long been acknowledged both in academia and practice (Ulrich, 1984). Indeed, the BE is known for affecting the safety and well-being of patients and caregivers (Zhang et al., 2019). There is also evidence that the clinical outcomes of patients might benefit from a supportive BE, which can involve, for example, views of external areas like gardens, and natural lighting (Sundberg et al. 2020b). The corresponding BE knowledge-base has evolved under the umbrella of Evidence-Based Design (EBD), which guides the stakeholders involved in the design of healthcare facilities (Ulrich et al., 2008; van Hoof et al., 2015; Zhang et al., 2019).

EBD uses a variety of methods such as interviews, questionnaires, focus groups, layout analysis, and simulation (Kumar et al., 2011; Sadek & Shepley, 2016). Those methods can be used for the identification of stakeholders' requirements (Van Hoof et al., 2015), which are defined as the expression of functions, attributes, and characteristics that a product or service must perform to meet a stakeholder's needs (Baldauf et al., 2021). Effective requirements management contributes to designs that account for Work-as-Done (WAD), which corresponds to what occurs in reality. WAD is in contrast to Work-as-Imagined (WAI), which corresponds to what managers or policy makers would aspire to being conducted or achieved (Braithwaite, 2018; Hollnagel, 2014).

However, BE design solutions are often based on WAI models that do not properly account for the reality of WAD (Rapport et al., 2020). As a result of this disconnection, staff adjusts their performance during the use of facilities (Borsci et al., 2018; Braithwaite, 2018). These adjustments include changes in the BE made by staff (e.g., in the layout of patient rooms), which create a misalignment between the BE-as-Imagined (BEAI) and the BE-as-Done (BEAD) (Ransolin et al., 2020). Changes in healthcare facilities also commonly stem from refurbishments for capacity expansion and technological upgrades to meet the requirements of a diversity of users and regulations (Shumaker & Pequegnat, 1989; Short et al., 2014).

These changes arise from the partly unpredictable interactions among people, technologies, processes, and the environment external to health services (Braithwaite, 2018; Carayon et al., 2014). These interactions, when considered holistically, are seen to be socio-technical, justifying the framing of health services as complex socio-technical systems (CSSs) (Churruca et al., 2019; Braithwaite et al., 2017). For this reason, complexity theory has been used as a lens to analyze a number of problems in health services (Tolf et al., 2020; Göras et al., 2019; Ferreira & Saurin, 2019). Like others (e.g., Brainard and Hunter, 2016), we adopt the term complexity theory as an umbrella that covers core principles of systems thinking, socio-technical systems theory, and adaptive complex systems. Complexity theory is systems-oriented, being primarily concerned with how elements (e.g., people, technologies, management routines) interact with each other and with the environment, giving rise to emergent system properties (Braithwaite, 2018).

This paper is concerned with one of the emergent properties of CSSs, namely resilient performance. From an organizational perspective, resilient healthcare is defined as the "ability of the healthcare system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required performance under both expected and unexpected conditions" (Hollnagel et al., 2013, p. xxv). Studies that explicitly address resilient performance and the BE are usually focused on coping with natural or man-made disasters (Achour & Price, 2010; Ochi et al., 2020; Ransolin et al., 2021; Capolongo et al., 2020; Keenan, 2020). These studies approach the BE from a technical rather than socio-technical perspective– e.g., the cooling of buildings to protect against climate change, heat waves, and power outages (Attia et al., 2021; Re Cecconi et al., 2018). However, everyday work with normal operational conditions also involves unwanted variabilities (e.g., scarcity of resources, efficiency pressures) that might be concealed due to successful resilient responses (Hollnagel, 2014). Kamara et al. (2020) expand on this point arguing that resilience relies on how the BE is adapted by its users on a daily basis.

Moreover, resilience is a proxy of concepts such as flexibility and adaptability, which are commonly addressed by EBD studies (Pati et al., 2008; Aalto et al., 2019; France et al., 2009). In this respect, there are studies that reviewed flexibility strategies to the design of healthcare facilities such as oversizing of load-bearing structures (Brambilla et al., 2021) and surplus capacity for heating, ventilation, and air conditioning (Carthey et al., 2011). These strategies "future-proof" health buildings to changes (Carthey et al., 2011). However, the implications to resilient healthcare need to be made explicit in the EBD literature, based on a socio-technical perspective. This drawback is addressed in this paper by using a transdisciplinary theoretical lens (i.e., complexity theory) that accounts for both the technical and social dimension of health services. Through this lens, resilient performance can be seen as a functional and dynamic system property (Hollangel, 2014). This implies that the investigation of the links between resilience and the BE needs to consider how people interact with the BE, rather than only considering what the BE is like from a static and technical perspective.

Against this backdrop, the research question addressed by this study is stated as follows: **How to develop built environment design knowledge that supports resilient performance during everyday work in health services?** This question is addressed through a systematic literature review of EBD. Guidelines for coping with complexity, which are logically related to resilient performance, are adopted as an analytical framework. These guidelines have been used by previous studies on resilient healthcare (Righi & Saurin, 2015; Bueno et al., 2019), including another systematic literature review, in which improvement interventions in intensive care units were assessed (Bueno et al., 2019). Those studies demonstrated the content validity of these guidelines and their utility for the identification of improvement opportunities from the resilience and complexity viewpoints.

3.2 GUIDELINES FOR COPING WITH COMPLEXITY

Although CSSs are self-organizing, they might be deliberately influenced through work system design (Plsek & Greenhalgh, 2001). Design guidelines are presented by several studies that use complexity theory as a theoretical lens. In this study, we use the guidelines compiled by Saurin et al. (2013), which emerged from a literature review of seminal texts on complexity theory (Perrow, 1984), principles for designing CSSs (Clegg 2000), management of complex systems in the BE (Rooke et al. 2008), and resilience engineering (Hollnagel et al., 2011). These guidelines (Table 4) have been used by several studies in health services in recent years (Saurin, 2021; Rosso & Saurin, 2018; Bueno et al., 2019; Mahmoud et al., 2021).

Guidelines for coping with complexity (Saurin et al., 2013; Bueno et al., 2019)	**Relevance of the guidelines for the BE in health services**
Guideline 1- Supporting visibility of processes and outcomes	
The functioning of CSSs should be intuitive for their users and real-time visibility should be given to both formal and informal work practices (Clegg, 2000; Galsworth, 2017). Informal practices may encompass useful innovations or create latent hazards.	The BE can either support or hinder the visibility of processes (e.g., patient care) and outcomes (e.g., safety performance indicators). For example, design decisions related to layout configuration usually have consequences for visibility. In turn, visibility can hinder patient and staff privacy.
Guideline 2 - Designing slack	
Slack is a mechanism for eliminating some interdependencies and reducing the propagation of variability (Safayeni & Purdy, 1991). This may be obtained through spare resources (e.g.	Health services are exposed to several variabilities such as sudden rises in demand, and varying patient profiles. Some of these variabilities must be considered in the BE design, by using slack

human, technical) which can be called on in times of need (Nohria & Gulati, 1996).	resources (e.g., facilities that can change their functionalities).
Guideline 3 - Encouraging diversity of perspectives when making decisions	
Diversity of perspectives may help to tackle uncertainty. There are some requirements for the implementation of this guideline: high levels of trust, low power differentials, and apt decision-makers (Page, 2010).	The BE design must account for the perspectives of the main groups of users, such as caregivers, administrative staff and patients. In addition, BE design must create spaces that facilitate collaborative work.
Guideline 4 - Monitoring and understanding the gap between WAI and WAD	
Monitoring and understanding the gap between WAI and the WAD sheds light on variabilities that otherwise may be taken for granted. Reasons for this gap should be investigated, as well as its consequences (Hollnagel, 2017).	The complexity of health services implies significant gaps between WAI and WAD. Similarly, the BE-as-Done (BEAD) corresponds to the actual space as adapted on a daily basis by people. The BE-as-Imagined (BEAI) corresponds to the designed spaces, defined prior to the use of the facilities (Ransolin et al., 2020).
Guideline 5 - Monitoring unintended consequences of improvements and changes	
Improvements and changes interact between themselves and with the environment, posing opportunities for unintended consequences (Perrow, 1984). These consequences may involve benefits or drawbacks (Ogrinc et al., 2015).	There might be trade-offs between the requirements of the BE users. Thus, BE design decisions that benefit a certain user may imply unintended consequences for others.

Table 4 - Guidelines for Coping with Complexity.

As discussed by Bueno et al. (2019), those guidelines are logically connected to the four abilities of resilient systems proposed by Hollnagel (2017). These abilities are: *respond* to both regular and irregular changes in working conditions; *monitor*, looking for possible negative or positive impacts on system performance; *learn,* representing the acquisition of experience from positive and negative events; and *anticipate*, expecting and preparing for system disruptions or opportunities. As an example of the relationships between the guidelines and the abilities, the visibility of processes and outcomes is a means for monitoring threats and opportunities.

3.3 RESEARCH METHOD

3.3.1 Selection of Publications

The selection of the publications followed the steps proposed by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method, developed by Moher et al. (2009). These steps are: (1) identification of the papers; (2) screening; (3) eligibility; and (4) inclusion (Figure 2).

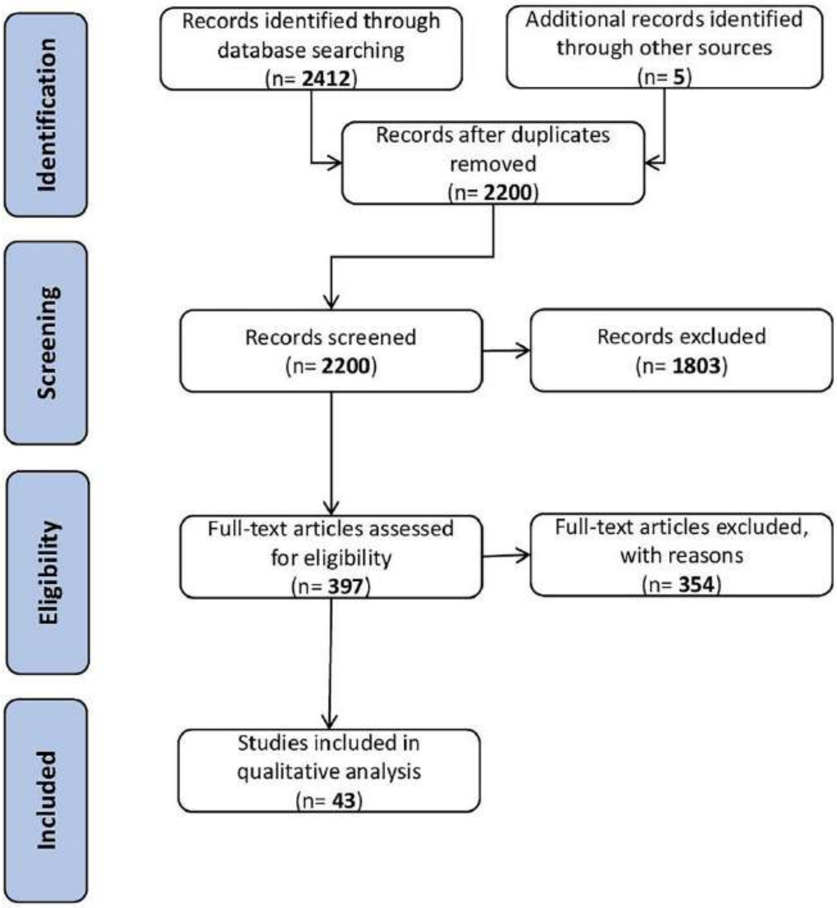

Figure 2 – Steps for the selection of papers.

In the identification step, carried out in September 2021, we searched for publications on seven major databases: Cochrane, Pubmed, Jstor, and Scopus, Web of Science, Sage, and Wiley. An adaptation of the PICO model (Population, Intervention, Control, and Outcomes) (Brown & Ecoff, 2011), which is used for searches in Evidence-based Medicine, was adopted for defining the keywords. Thus, we defined keywords for the study object, context, approaches, impact, and stakeholder, which respectively resemble intervention, control (for context and approaches), outcomes, and population. The search string was composed of words related to these groups (Figure 3). It is worth mentioning two keywords potentially relevant to BE resilience that were not accounted for: (*i*) disasters – this was out of the scope for the research question concerned with everyday work; and (*ii*) post-occupancy evaluation – this was assumed to be applicable to EBD studies in general with no specific relevance to resilience.

Figure 3 - Search String.

Initially, 2412 records were identified from the selected databases, and five sources were manually added. The publications were not limited by year. The filters for searching papers in each database were: (1) English language; and (2) a set of subject areas: engineering, social science, business and management, arts and humanities, multidisciplinary, psychology, and decision sciences. After the identification of duplicated records, 219 publications were excluded.

In the screening step, the remaining 2200 articles were analyzed, based on their title, abstract, and keywords, considering four exclusion criteria: (i) non-scientific texts; (ii) conference proceedings; (iii) literature reviews; and (iv) content unrelated to healthcare facilities (e.g., ethical aspects), or the research aims (e.g., risk analysis). Based on these criteria, 1803 publications were excluded. Then, in the eligibility step, the 397 resulting publications were scanned in order to exclude papers that did not contain any of the following keywords in the full text: Complex*; Resil*; Flex*; Adapt*; Flow; Evidence-based Design (EBD). Finally, in the inclusion step, 43 publications were selected and analyzed.

3.3.2 Data Analysis

3.3.2.1 Overall Characterization of Publications.

An overall characterization of the publications was made based on the following criteria: (i) bibliometric information; (ii) description of the health service that was the focus of the study; (iii) theoretical background adopted, in addition to EBD; (iv) outcomes emphasized (well-being, efficiency, and safety); and (v) main users focused on (patients and families or healthcare staff).

3.3.2.2 Identification and Analysis of the Design Knowledge.

The selected articles were subject to a content analysis (Pope et al., 2000), which encompassed: familiarization, identifying themes, coding, charting, and mapping and interpretation. Familiarization involved reading the papers in order to gain an understanding of the recurring themes. Themes defined upfront by the researchers were imposed on the data as a heuristic device. The themes corresponded to the five previously described complexity guidelines.

The coding stage was carried out in four steps with different levels of abstraction, which corresponded to a hierarchical structure composed of design meta-principles, design principles, design prescriptions, and practical examples. Initially, at the highest abstraction level, the design meta-principles, excerpts of text related to the use of the five complexity guidelines were identified. Next, these excerpts were re-interpreted in terms of their underlying implications for the BE, giving rise to design prescriptions. Then, design prescriptions concerned with similar themes were grouped into categories. Each of these categories was named as a design principle that reflected the common theme shared by the prescriptions. Finally, for each design prescription, practical examples were retrieved from the papers. As an illustration of this coding process, the following excerpt of text, which is related to the meta-principle supporting visibility of processes and outcomes, was retrieved from France et al. (2009): "each floor uses a theme and a neighborhood system (i.e., defined by unique floor color schemes and by animal or nature signage) to guide young patients through their clinical areas". This excerpt was re-interpreted as the following design prescription: "facilitate spatial navigation". The use of animal or nature signage is a practical example of this prescription. Then, similar prescriptions were grouped, giving rise to the design principle "supporting wayfinding".

This coding process was initially carried out separately by two of the authors (NR and CMZ), both architects with a background in healthcare research. They met on several occasions (20 meetings in total of 1-hour duration) to compare their codifications and reach a consensus. This coding was further reviewed by a senior researcher (TAS), who was a co-author of all earlier studies related to the complexity guidelines, resulting in additional adjustments.

The thematic analysis continued with the charting phase, which synthesized findings from the previous stages. For each design meta-principle, the corresponding principles, prescriptions and examples were schematically represented (see the results section). Finally, at the mapping and interpretation stage, results were discussed in light of previous studies and reflections were made on the nature and role of the elicited design knowledge in resilient healthcare.

3.4 RESULTS

3.4.1 Overview of the publications

The 43 papers included in this review were published since 2008, with 15 articles published in 2019 and 2020, and three published in 2021. Papers were published in 17 journals, mostly in Health Environments Research & Design (HERD) (26). Regarding the healthcare units that were the focus of investigations, these were distributed as follows: intensive care units (10), operating rooms (10), wards (six), emergency departments (four), outpatient clinics (three), childbirth facilities (two), cancer care centers (two), non-clinical areas such as public spaces and corridors (one), and an oncology unit (one). Four studies did not inform the studied unit.

Ownership, in addition to whether institutions are teaching or non-teaching, are other relevant contextual characteristics of the studied health services, even though several papers did not present information on them. As for ownership, nine of the studied health services were owned by governments and 13 by private organisations. In turn, 24 studies were carried out in teaching services and four in non-teaching services. Regarding size, there were two small-sized facilities (i.e., comprising up to 50 beds), two medium-sized (from 51 to 150 beds), and 27 large-sized (151 to 500 beds). This categorization of health services according to the size of facilities is adopted by the Ministry of Health in Brazil. Some papers reported studies in more than one facility and 15 studies did not present information on the number of beds. In fact, there was no standardized approach for describing the healthcare facilities investigated. Some studies defined the size of the facility in terms of the number of employees and patients (e.g., Baumgart et al 2009), others in square meters (e.g., Aalto et al., 2019), and others did not mention the physical positioning of the studied unit in relation to the rest of the healthcare facility. The lack of information about the context of the study is a drawback, because the complexity level of the health service is dependent on its size and functioning (Perrow, 1984). Public and teaching health services present complexity characteristics distinct from private and non-teaching, which can influence the BE and resilience. Public services have less control on their demand as they may not so easily close their doors to the external public, which has implications for overcrowding. Similarly, teaching services tend to have a higher turnover of staff, which makes wayfinding even a more important consideration.

An analysis of the theoretical background adopted by the papers was also conducted. Besides referring to EBD, papers addressed patient-and-family-centered care (16) (Choi & Bosch, 2013; France et al., 2009), the complexity of health services (11) (Rapport et al., 2020; Ransolin et al., 2020), safety science (7) (Pati et al., 2016; Sundberg et al., 2020a), human factors and ergonomics (6) (Platt et al., 2017; Battisto e al., 2009), and lean healthcare (3) (Karvonen et al., 2017; Copeland & Chambers, 2017). Post-occupancy evaluation was a methodological approach (10 papers) common to several of those theoretical backgrounds.

As for the outcomes emphasized by the studies, 40 focused on well-being, 31 on efficiency, and 22 on safety. Regarding the main users, 37 articles focused on patients and families, while staff members were the focus of 36 papers. Most of the studies were concerned with more than one of these outcomes. Additional characterization of the 43 papers can be found in the Supplementary Material (Appendix C).

3.4.2 Design Knowledge for Built Environment Supportive of Resilient Performance

The resulting knowledge structure elicited from the literature review is presented next according to its most salient logical relationships with four out of the five complexity guidelines (i.e., design meta-principles). The guideline on unintended consequences is not directly associated with any specific set of design principles as it permeates all other guidelines. The implementation of the other guidelines implies changes in the work environment, which triggers new interactions and possible unintended consequences (Righi & Saurin, 2015).

3.4.2.1 Meta-Principle 1: Supporting visibility of Processes and Outcomes

Designing Layouts that Support Resilience. This design principle was the most cited (35 out of the 43 papers) and encompasses three design prescriptions and 16 examples (Figure 4). The most cited design prescription (25) in this group was to "ensure patient privacy without hindering visibility" (Naccarella et al., 2019). An implementation example is the design of a zone outside the patient room that allows visibility to the inside, making it possible the visual monitoring of the patient while avoiding constant entries in the patient room (Rich and Day, 2008). The prescription "designing layouts that reduce motion and transportation activities" was cited by 24 papers (Colman et al., 2020; Greer et al., 2021). Resilient performance benefits from this prescription as the efficiency gains from less motion and transportation support quick responses to abnormalities. It can be put into practice, for example, through radial layout design that allows direct visual and physical access to all patient rooms from the nursing station (Pouyan et al., 2021). Layout design is also concerned with "creating spaces for socialization", a design prescription mentioned by four papers (Schaumann et al., 2020). Caregivers need to exchange information to improve teamwork and establish bonds (Fay et al., 2017). Furthermore, during the rehabilitation period, patient communication and integration with others is beneficial for clinical outcomes (e.g., interactions among patients and their next of kin). Dayrooms can reduce the obstructions in the corridor by providing specific zones for these interactions (Schaumann et al., 2020).

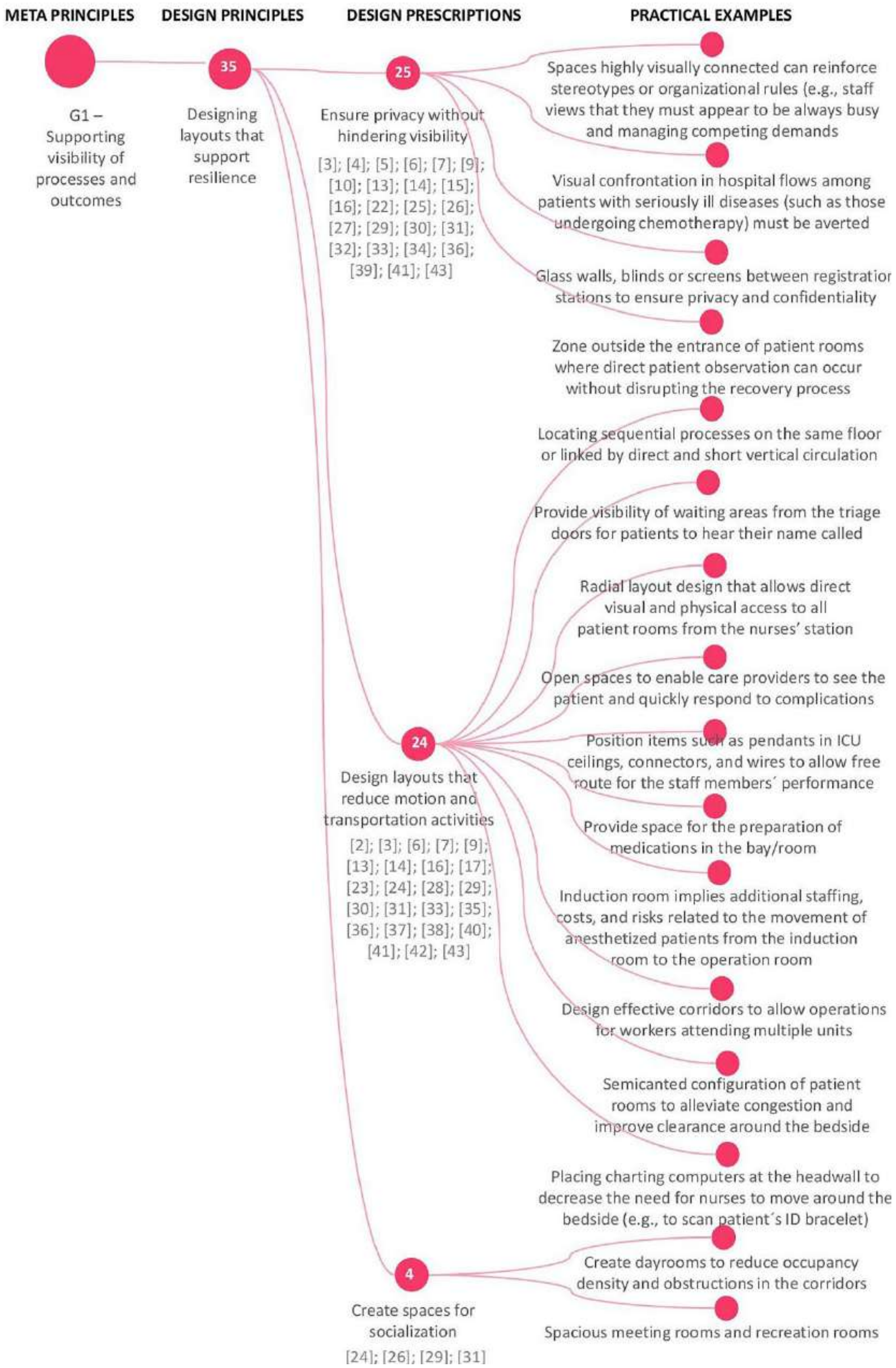

Figure 4 - Built environment design knowledge related to designing layouts that support resilience. Note. The numbers within the circles indicate the citation frequency.

Supporting Wayfinding. This design principle was cited by 30 papers associated with five design prescriptions and 16 examples (Figure 5). Wayfinding contributes to create informative, intuitive, and accessible healthcare environments, especially in communal spaces. Regarding this principle, the most cited prescription (22) was "facilitating spatial navigation" (Dehe & Bamford, 2017). A practical example is the provision of maps or signalized pathways in corridors and public spaces to allow easily navigable interfaces between expansions built over time (Prugsiganont & Jensen, 2019). To "include positive distractions in the BE" is a prescription mentioned by ten papers (Sundberg et al. 2020b). The 'typical hospital' atmosphere is highly disliked by vulnerable patients (Jellema et al., 2020). Thus, BE attributes that provide visual impact for users are sources of positive distractions (e.g., colors, exterior views) that help to mitigate boredom, anxiety, fear, and even pain (France et al., 2009; Sundberg et al. 2020b). These distractions are related to wayfinding as they: (*i*) imply distinctive, and sometimes unique characteristics (e.g., artwork); and (*ii*) improve the patient health condition (France et al., 2009). Both of these implications can assist in spatial awareness.

The prescription "zoning according to user profile or functionality" was cited by nine papers (Copeland & Chambers, 2017) and can be illustrated by separating areas according to patient acuity levels (Pati et al., 2016)."Facilitating patient transportation between hospital units" was cited by five papers (Holmdahl & Lanbeck, 2013) and can be exemplified by the provision of large doorways and corridors disposed in line to facilitate the maneuver of patients, equipment, and personnel (Colman et al., 2020). The prescription "providing spatial reminders of what to do and where to be for staff" (three citations) (Waggener et al., 2021) can involve the use of signage and environmental cues to support the memorization of activities and their sequence (Rapport et al., 2020). An example of using this prescription involves placing sinks and dispensers in anterooms, to act as spatial reminders to hand hygiene at the right time and place- e.g., before entering isolation or operation rooms (Holmdahl & Lanbeck, 2013).

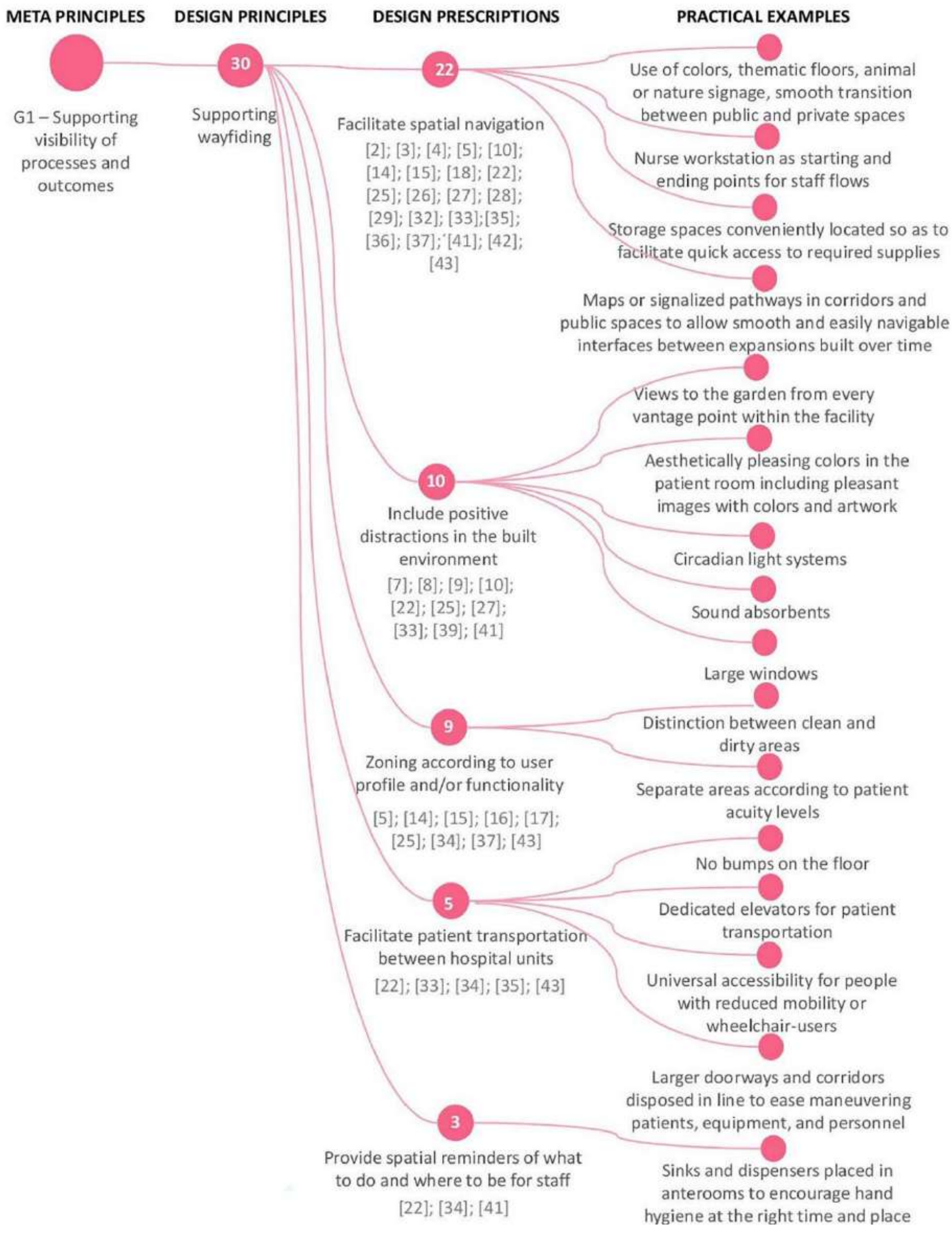

Figure 5 - Built environment design knowledge related to supporting wayfinding. Note. The numbers within the circles indicate the citation frequency.

3.4.2.2 Meta-Principle 2: Designing Slack

Providing Flexibility while Maintaining the Same Functionality. This design principle was cited by 20 papers, including three design prescriptions and 7 examples (Figure 6). Adaptability benefits from the prescription "creating patient rooms adaptable to different patient acuity levels" (10) (Blennerhassett et al., 2018). An example of using this prescription is the placement of additional doors in the isolation rooms, which can be used when the patient profile changes (e.g., infectious disease is healed) and thus the original access through the anterooms is no longer necessary (Holmdahl & Lanbeck, 2013). Further application of this prescription refers to times of extensive family involvement or terminally ill patients. In these circumstances, it might be useful to design double-bed rooms with a sliding door in-between the beds for the adaptability of large single rooms to small rooms (Apple, 2014). Another prescription related to this principle is "allowing the customization of spaces according to patient and family preferences" (10) (Aalto et al., 2019). The customization of spaces can be achieved by the use of furniture, lighting, and temperature according to the needs expressed by patients and family members (Rich & Day, 2008).

In turn, the expandability of spaces can be created by designing modular rooms that are easily enlarged to accommodate more patients and services (Pati et al., 2008). This is a practical example of the prescription "design for building expansion in the short and long-term" (6).

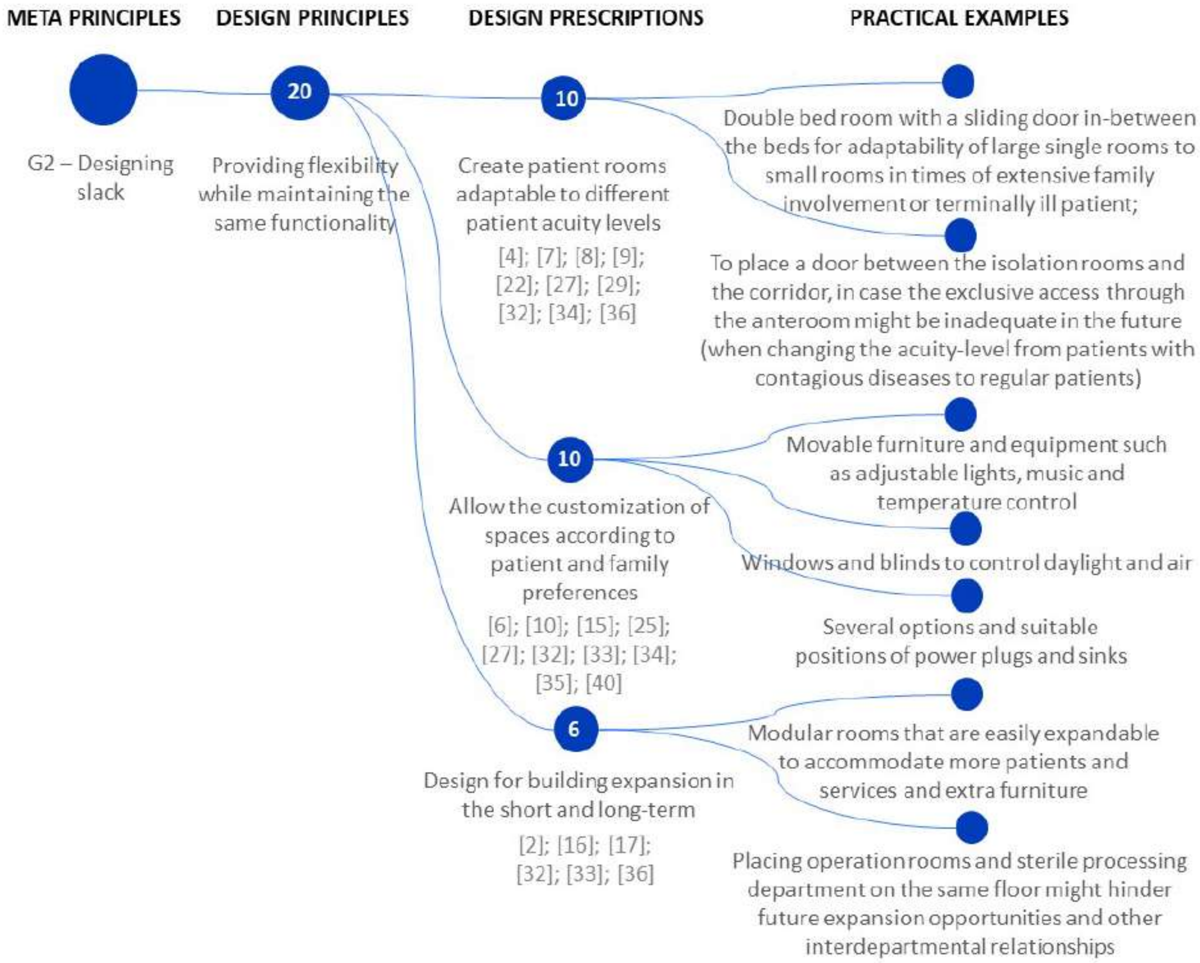

Figure 6 - Built environment design knowledge related to providing flexibility while maintaining the same functionality. Note. The numbers within the circles indicate the citation frequency.

Providing Flexibility for Changing Functionalities. This design principle was cited by 29 papers, including three design prescriptions and five examples (Figure 7). The lack of BE preparedness for changing functionalities can result in corridors being used as storage spaces for wheelchairs, beds, or medical supplies (Prugsiganont & Jensen, 2019). As such, the design of "multi-purpose furniture, rooms, and equipment" is the most cited prescription (23) related to this group. It can involve, for instance, adaptable beds for different patient needs (Plough et al., 2019).

In turn, the prescription "allocating dedicated time and staff for managing the transition to new workspaces" (7) is concerned with the transition period to new facilities, which may disrupt daily activities and put an extra burden on caregivers (Copeland & Chambers, 2017). As a result, the use of dedicated staff members to manage the move to the new facilities is recommended (Lin et al., 2016). Although this prescription is process rather than product-oriented, we opted for including it as transitions to new workspaces are commonplace in healthcare facilities, often implying in improvisations and operational difficulties during the change period.

As for the prescription "creating barriers for the prevention of undesired interactions and variability propagation" (5), it is particularly useful for coping with infectious patients. These barriers can be, for example, balconies that facilitate patient transportation and promoting family and supplies access (Holmdahl & Lanbeck, 2013). This prescription was associated with the principle on changing functionalities as the said barriers can be either removed or used for non-anticipated purposes provided the spaces are occupied by non-infectious patients.

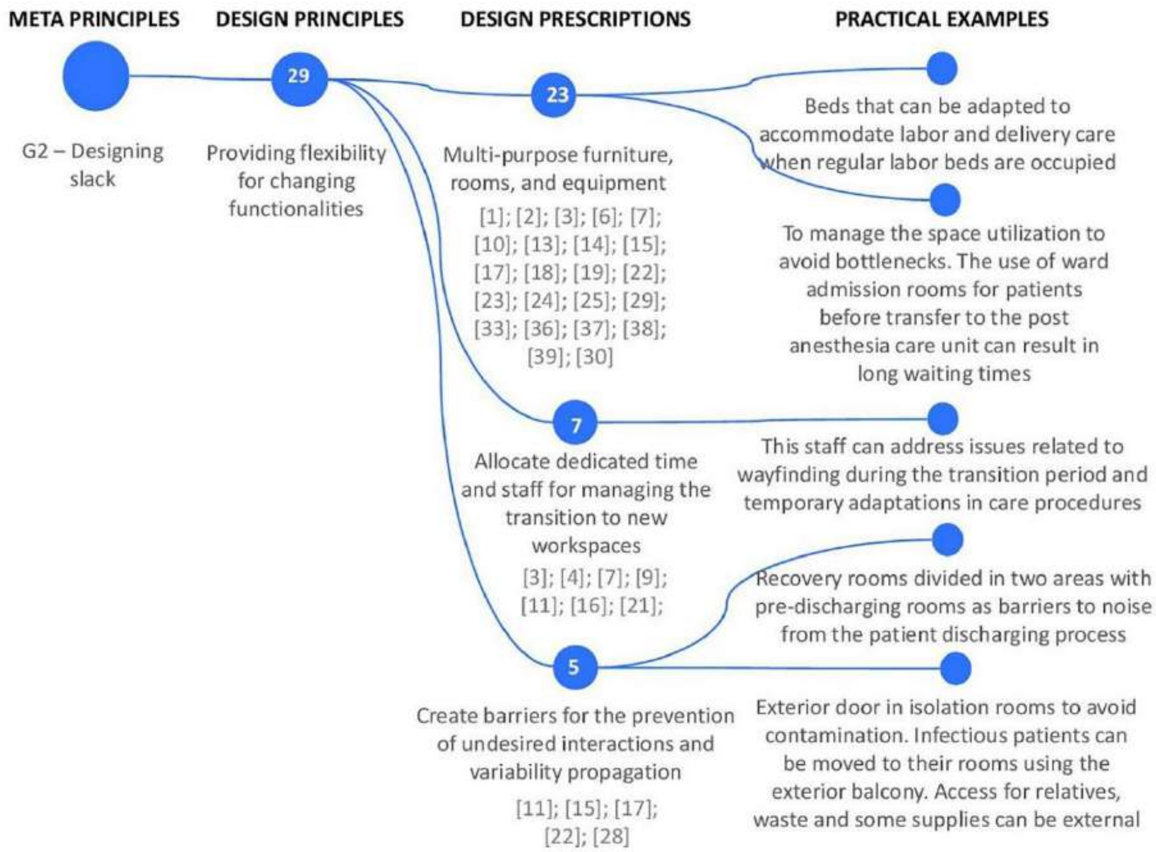

Figure 7 - Built environment design knowledge related to providing flexibility for changing functionality. Note. The numbers within the circles indicate the citation frequency.

3.4.2.3 Meta-Principle 3: Encouraging the Diversity of Perspectives when Making Decisions

Leveraging Patient and Family Perspectives. This design principle was cited by 19 papers, including two design prescriptions and five examples (Figure 8). "Providing dedicated space for family contact with staff" is the most cited prescription (15). Rippin et al. (2015) argue that dedicated spaces for families to contact staff create an environment where people feel welcome to initiate conversations, while still giving visibility to the patient room (e.g., alcoves just outside patient rooms). In addition, staff may benefit from family-friendly spaces where families can report patient's history and daily routine, being a valuable source of information in clinical decision-making (Rippin et al., 2015). It involves providing suitable spaces, such as single-bed rooms or spacious rooms, to encourage families to stay longer and assist patients in physical activities (Choi & Bosch, 2013). Family members can help by feeding, and bathing the patient while providing emotional support (Blennerhassett et al., 2018). Also, amenities and appropriate furniture (e.g., recliner chair and storage space for belongings) contribute to family and patients being proactive in care delivery (Harte et al., 2016).

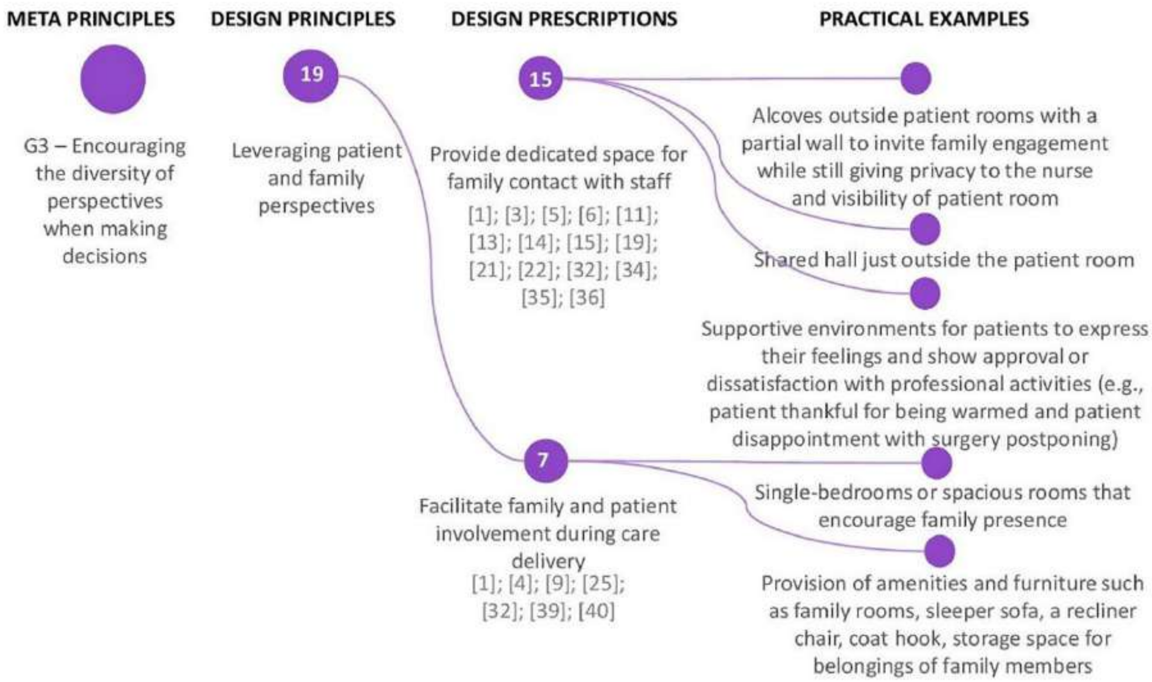

Figure 8 - Built environment design knowledge related to leveraging patient and family perspectives. Note. The numbers within the circles indicate the citation frequency.

Leveraging Staff Perspectives. This design principle was mentioned in 20 papers, encompassing two design prescriptions and four practical examples (Figure 9). The prescription "mentioned by 16 papers, is aligned to the growing need for multidisciplinary care (Lin et al., 2016; Waggener et al., 2021). The literature indicates that healthcare facilities should provide proper spaces for information exchange amongst staff members (Naccarella et al., 2019). Open rooms are more conducive to teamwork since they support social interaction and face-to-face communication (Fay et al., 2017). By contrast, single-bed rooms reduce opportunities for interactions between staff (Apple, 2014), which may reduce opportunities for peer-mentorship and interaction between experienced and novice nurses (Van Heuvelen, 2019).

"Creating spaces for resting", a prescription cited by six papers, is important for reducing fatigue and therefore improving the quality of care delivered (Plough et al., 2019). For instance, by providing break areas and staff restrooms for professionals to relax and be free from constant work interruptions (Pati et al., 2008).

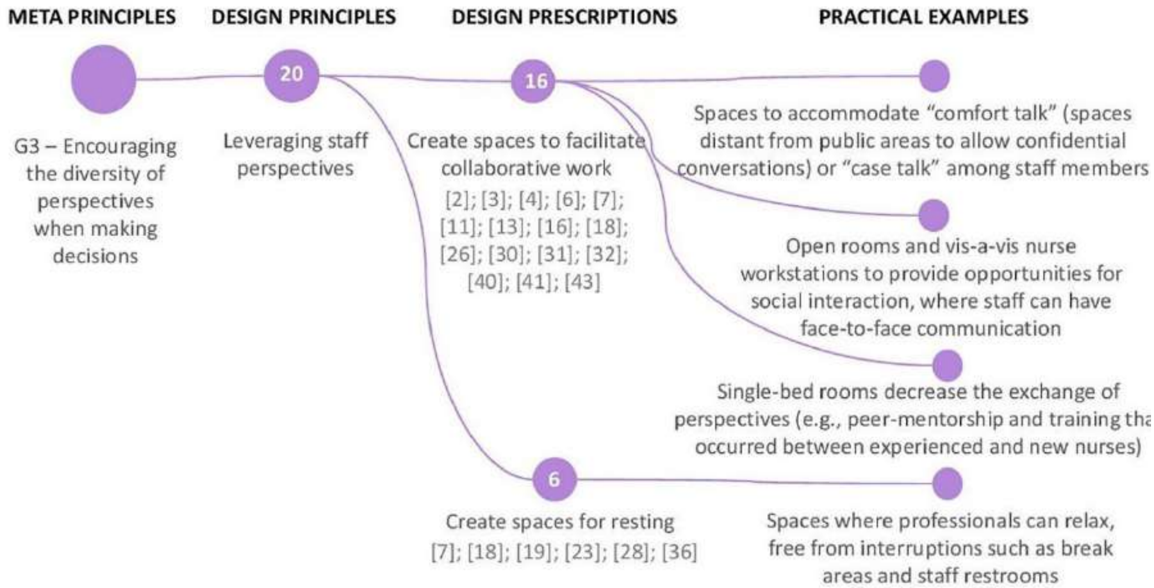

Figure 9 - Built environment design knowledge related to leveraging staff perspectives. Note. The numbers within the circles indicate the citation frequency.

3.4.2.4 Meta-Principle 4: Understanding the Gap between the WAD and the WAI

Reconciling the Gap between the Built Environment-as-Done (BEAD) and the Built Environment-as-Imagined (BEAI). This design principle was referred to by 24 papers, counting on three design prescriptions and five examples (Figure 10). The prescription "design for compatibility between the built environment and the adopted care model" is cited by 18 papers (Pouyan et al., 2021). BE design can facilitate or hinder organizational and personnel ability to change workload demands, staffing patterns, and operational management (Pati et al., 2008). For instance, in single-bed rooms, as opposed to open bays, caregivers can feel isolated and have difficulty in getting assistance (Baumgart et al., 2009). Another example refers to the choice between decentralized and centralized nurse stations. In general, decentralized nurse stations are preferable for care models that require nurses to focus on their own patients (Real et al., 2017). However, although decentralized stations bring nurses into closer contact with their patients, they are said to hinder teamwork (Real et al., 2017; Copeland & Chambers, 2017; Waggener et al., 2021).

The prescription "learning from workarounds and improving future designs (or re-design the existing workspaces)", mentioned by 12 papers (Fay et al., 2017), is central to bridge the gap between the BEAD and the BEAI. When spaces are unfit for use, staff members employ workarounds to perform their activities (Rapport et al., 2020). However, workarounds may impact patient care (Pati et al., 2016). An example of workaround is the use of the ceiling light to block the air-conditioning exit when the operation room is too cold - as a consequence, the surgeon might have the visibility of the surgical camp impaired by the positioning of the lights (Rapport et al., 2020). To avoid frequent workarounds, WAD should be considered since the early BE design stages and monitored during building usage (Ransolin et al., 2020). Finally, "accounting for anticipated or likely changes in regulations" is a design prescription cited by six papers (Pati et al., 2012). These changes can be anticipated based on trends from other countries and practices adopted by leading healthcare organizations (Holmdahl & Lanbeck, 2013).

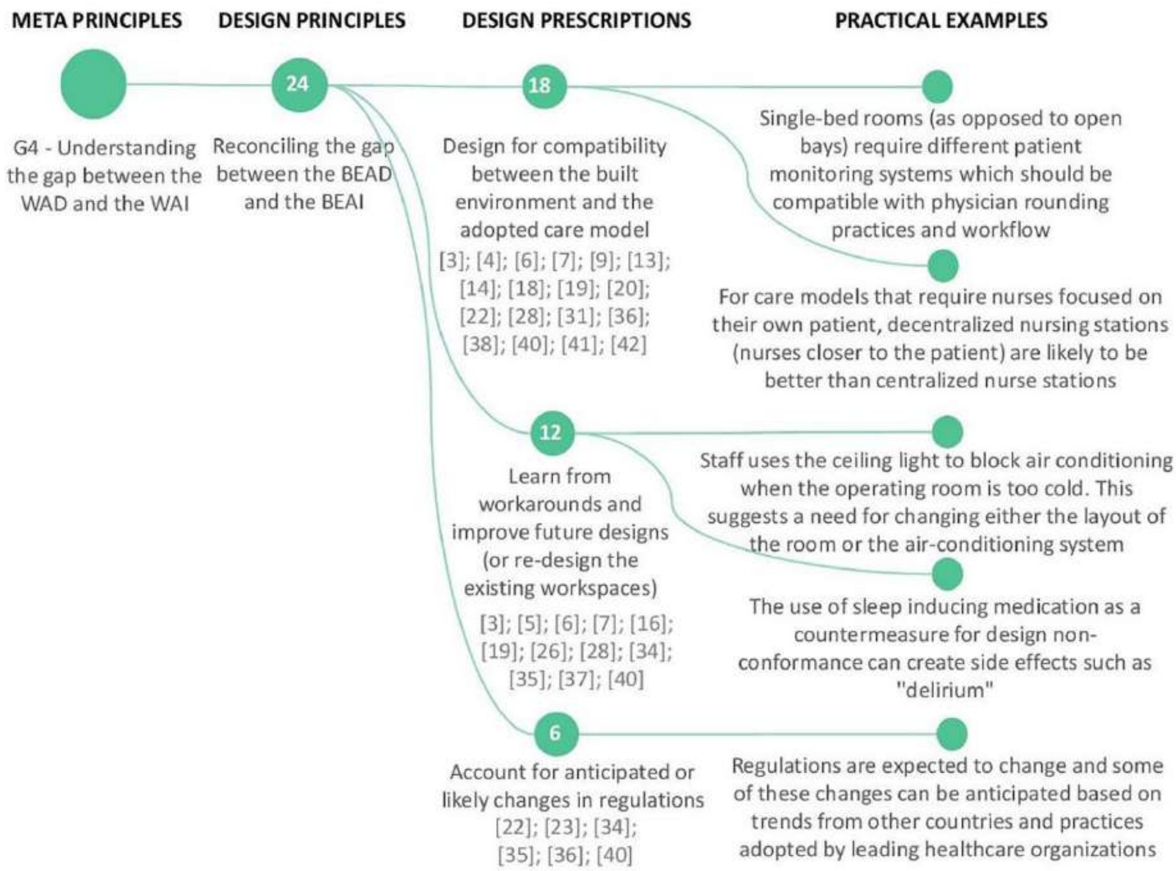

Figure 10 - Built environment design knowledge related to reconciling the gap between the BE-as-Done (BEAD) and the BE-as-Imagined (BEAI). Note. The numbers within the circles indicate the citation frequency.

3.5 DISCUSSION

The nature and role of the elicited design knowledge in resilient healthcare is discussed in this section. Initially, it is worth reinforcing that resilient performance is a functional property of complex systems (Hollangel, 2014). Therefore, the BE itself cannot be resilient because it is static when not in use. The BE can at best create conditions that support resilient performance. Thus, our findings are not meant to be used for the design of the BE as a purely technical infrastructure. By contrast, the design knowledge might contribute to address a drawback in healthcare facilities in general, namely the lack of integration between the design of their technical and functional dimensions (Baumgart et al., 2009; Ransolin et al., 2020). In this respect, the design principles can be jointly used (and play a moderating role) with other sets of principles mostly focused on either the technical or the social portion of health services. As an example of mostly technically-oriented principle, BE design must avoid the creation of surfaces that facilitate the accumulation of dust, a possible source of contamination (Aalto et al., 2019). As an example of a functionally-oriented principle, nursing staff must carry out a series of safety checks before administering drugs to patients (Pickup et al., 2017). The principles proposed in this paper are midway between these two examples, addressing technical elements that support functions.

Another characteristic regarding the elicited design knowledge is that it is not universally effective nor necessary. A BE supportive of resilient healthcare tends to grow in importance as the complexity of the health service increases (Righi & Saurin, 2015). Organization size, ownership, and teaching or non-teaching service are possible proxies of the complexity level (Bueno et al., 2019). The guideline on unintended consequences also acts as a reminder of the contingent character of the design knowledge (Perrow, 1984).

The design knowledge is also fractal, which means that it is possibly applicable across different scales. In resilient healthcare, the micro, meso, and macro levels have been a commonly used framework to discuss fractality (Berg et al., 2018). However, the selected papers were mostly concerned with the micro level, which focuses on individual hospital units or spaces. For example, Pati et al. (2016) explored the security implications of BE attributes in an emergency department. The meso level is concerned with two or more units at the same time, or even with the hospital as a whole. For example, Pouyan et al. (2021) focused on the hospital wayfinding behavior regarding circulation complexity. The macro level, which encompasses a network of health services at the regional or national level, was virtually neglected by the selected studies. As an illustration of the applicability of the design knowledge to the macro level, wayfinding also applies for guiding patients that are referred from one hospital to another - e.g., signage and visual identity can help patients to quickly find their way from the hospital they traditionally visit to another that is new for them. Similarly, it is not uncommon that the same staff work part-time in different hospitals (Brewer et al., 2012). Perspectives and experiences acquired in one institution may affect their performance in the other, thus playing out at the macro level.

The design knowledge is also logically related to the four abilities of resilient systems mentioned in section 2. These relationships can be more precisely illustrated by the design prescriptions and their practical examples. As for the respond ability, the prescription "design layouts that reduce motion and transportation activities" is useful as it enables providers to quickly **respond** to patient complications (Real et al., 2017). In turn, regulations are susceptible to changes due to technological trends and new practices adopted by leading healthcare institutions. Then, the design prescription "account for anticipated or likely changes in regulations" (Pati et al., 2012) has a straightforward relationship with the **anticipate** ability. This relationship is further illustrated by Holmdahl & Lanbeck (2013): they argue that, cost considerations set aside, patient rooms should be constructed with negative pressure as antimicrobial resistance is expected to grow in importance in the foreseeable future.

The resilience abilities of **monitoring** and **learning** are mostly logically related to the design principle "reconciling BEAI and BEAD", which implies a gap between design and reality. Therefore, the gap should be continuously monitored, which can be made easier through the consultation of diverse perspectives during everyday clinical work and the visibility of processes and outcomes (Apple, 2014). Information produced from this monitoring sets a basis for learning. The prescription "learn from workarounds and improve future designs (or re-design the existing workspaces)" exemplifies how our findings are relevant to the learning ability of resilient systems. Overall, the aforementioned discussion suggests that the elicited design knowledge is useful for both the design and operation phase of healthcare facilities. This is consistent with the functional nature of resilient performance, which evolves along the life-cycle of systems (Hollnagel, 2012; Bueno et al., 2019).

3.6 CONCLUSIONS

This study was guided by the following research question: how to develop built environment design knowledge that supports resilient performance during everyday work in health services? This question was addressed through a systematic literature review of 43 papers. The hierarchical structure that resulted from this review provided a meaningful organization to information that was so far fragmented in the EBD literature. It was comprised of four meta-principles, 7 design principles, 21 design prescriptions, and 58 practical examples. Two design principles stood out as the most used in the selected papers: designing layouts that support resilience (35 out of 43 papers); and providing flexibility for changing functionalities (29 out of 43). Both principles account for the changing nature of spaces in healthcare, which stresses their relevance in light of resilient healthcare. The principles on patient and family perspectives were the least used (19 papers), along with staff perspectives (20 papers).

The design knowledge emphasizes the interactions between the BE as a physical infrastructure and the functions that it supports. Therefore, the findings of this study might be useful not only to architects but also to other stakeholders. For example, designers of health services might use the design knowledge to explore the interactions between the BE and the flows of people and supplies. In the same vein, regulators may obtain insights for the introduction of resilience requirements in regulations related to the BE. Furthermore, our proposal might be interpreted as a knowledge template that can be continuously updated based on the experience of practitioners and academic research.

Two limitations of this study should be stressed. First, as it occurs with any systematic literature review, the adopted search string, inclusion and exclusion criteria imply that we set boundaries to our review and some relevant works may not have been considered. However, as mentioned above, the design knowledge might be updated based on further studies and changes in the criteria for selecting the papers, although preserving its logic. Second, although the review's interest in health services, in general, makes it relevant to a broader audience, it limits the exploration of particular services such as ICUs.

Several opportunities for future studies resulted from this paper. These are: *(i)* to use the compiled design knowledge for the development of tools for assessing new or existing designs, in order to verify the extent to which they support resilient healthcare; *(ii)* to carry out case studies of specific health services, in order to gain insight into how contextual factors (e.g., private versus public, teaching versus non-teaching) influence the uptake of design knowledge; *(iii)* to explore how the design knowledge can be used during the process of requirements management; *(iv)* to investigate the applicability of design knowledge to the macro level of health services, which would complement the emphasis on the micro and meso levels of the papers selected in this review; *(v)* to review design principles that are largely technically-oriented, stemming from areas such as BE resilience to disasters and flexibility, assessing their relationships with the design knowledge proposed in this paper; and *(vi)* to develop tools to disseminate the findings of this review to practitioners, in accessible language and formats that can be easily applied in their everyday work.

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4 PAPER II – Case Study I

The design knowledge derived from the systematic literature review is a starting point for the development of more context-specific contributions. Based on this, this chapter presents the development of BE design knowledge supportive of RP in internal hospital logistics. A case study was conducted in the common areas that involve service flows to and from an ICU of a large public teaching hospital. Design principles from the previous paper were used for data analysis, and the main findings gave rise to new prescriptions and practical examples also stressing the relationships between these and specific hospital areas and service flows.

The paper was published in Applied Ergonomics after thesis defence and corrections – please see Appendix I for the PDF of the publication. The title of the paper and other minor adjustments to fit the journal reviewer´s comments were made and can be seen in Appendix I. A poster with the primary findings was presented at a national and an international conference (citations below). The journal text has been formatted to fit these pages.

Paper citation: Ransolin, N., Saurin, T. A., Clay-Williams, R., Formoso, C. T., & Rapport, F. (2024). A knowledge framework for the design of built environment supportive of resilient internal logistics in hospitals. *Applied Ergonomics*, 116, 104209.

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Supplementary Material - Appendix E

Authorship statement - Appendix F

Presentations - Appendix H:

Ransolin, N., Saurin, T.A., Clay-Williams, R. Formoso, C.T., Rapport (2023). Framework for the Built Environment Supportive of Resilient Performance in the Connecting Areas of an Intensive Care Unit. In: *39th International Conference of the Society for Quality in Health Care (ISQua).* (Poster session). Seoul, Republic of Korea.

Ransolin, N., Saurin, T.A., Clay-Williams, R. Formoso, C.T., Rapport., F. (2023). The Built Environment Knowledge for Resilient Performance in Hospital Internal Logistics. In: *EnCouRage Symposium* (Poster session). Faculty of Medicine, Health and Human Sciences, Macquarie University. Sydney, 2023.

Paper as published: Appendix I

Built Environment Design Knowledge supportive of Resilient Performance in Hospital Internal Logistics

Natália Ransolin, Tarcísio Abreu Saurin, Robyn Clay-Williams, Carlos Torres Formoso, Frances Rapport

Abstract

Internal logistics is crucial for hospitals, occurring within facilities that pose constraints and opportunities, demanding resilient performance (RP) to adapt to dynamic conditions and balance safety and efficiency pressures. However, the role of the built environment (BE) to support RP is not explicitly analysed in the hospital logistics literature, which is usually limited to discuss BE in terms of layout and routing issues. To address this gap, this study presents a BE design knowledge supportive of RP in internal hospital logistics. The design knowledge was developed based on a study in a large teaching hospital, encompassing 11 service flows of people and supplies between an intensive care unit and other units. Data collection was based on 30 interviews, documents such as floor plans, and observations of logistics activities. Seven BE design principles developed in a previous study, concerned with RP in general but not focused on logistics, were adopted as initial themes for data analysis. Results of the thematic analysis gave rise to a design knowledge composed of seven design prescriptions and 63 practical examples of BE supportive of RP in hospital internal logistics. The paper discusses how these prescriptions and examples are connected to resilience theory, and illustrates the consequences of neglecting BE attributes. The design knowledge is new in the context of internal hospital logistics and offers guidance to both BE and logistics designers.

Keywords: built environment; design; hospital logistics; resilience.

4.1 INTRODUCTION

Health services have long been acknowledged as complex systems that display a myriad of manifestations of resilient performance (RP) (Braithwaite, 2018), defined as the expression of how systems cope with both expected and unexpected conditions while maintaining the delivery of the required outputs (Hollnagel, 2017). RP is an emergent property arising from the dynamic interactions between diverse technical, social, and organizational elements of health services, which are subject to the influence of the external environment (Wachs et al., 2016). The built environment (BE) is a key technical element of most health services, as it has a strong impact on the service efficiency, safety, and resilience (Machry et al., 2021). This paper is concerned with RP that stems from the interactions between people and the BE of hospitals, which comprises the physical assets such as buildings, utilities, furniture, and signage. The BE role in the RP of health services has been investigated mostly in the realm of coping with natural or man-made disasters (Keenan, 2020; Ochi et al., 2020). However, RP is also necessary and present during everyday work, once resilient health services should monitor, anticipate, respond, and learn from both expected and unexpected variability (Hollnagel, 2017).

Earlier studies of BE and RP in health services, however, pay little heed to the internal logistics of hospitals, defined as the functions of purchasing, moving, catering, handling, and storage of physical entities such as materials, equipment, and people (Jawab et al., 2018; Moons et al., 2019). Several requirements must be fulfilled by those functions, such as to use the shortest possible routes between suppliers and customers, to follow standardized routines to the possible extent, and to deliver according to customers´ demands (Moons et al., 2019; Volland et al., 2017).

This research study focuses on the logistics functions that take place in the areas that connect the hospital units such as corridors, elevators, stairways, accesses in general, and other common areas. Despite its importance, the role of the BE is not explicitly addressed in the hospital logistics literature, although it is implicit in the discussion of layout and routing (Prugsiganont and Jensen, 2019). This is a narrow perspective that does not account for the complex activities that occur in the connecting areas (Machry et al., 2022). For instance, these areas can be turned into clinical workspaces due to necessity – e.g., they may be used as waiting areas for patients before exams, and critically-ill patients may need care during their transportation (Copeland and Chambers, 2017). Further, similar to other activities in health services, those related to internal logistics display RP due to variabilities that challenge the standardized operating procedures – e.g., the standard routes may be blocked, there may be sudden surges of demand, or signage may be outdated (Capolongo et al., 2020). Nevertheless, both in healthcare and other sectors, the literature stresses RP in the external logistics, related to what occurs in-between the supplier and client facilities (Komljenovic, 2021). This is understandable as external logistics are vulnerable to high-profile events (e.g., strikes, natural disasters, pandemics) that simultaneously affect a large number of companies (Ivanov, 2021).

Therefore, it is important to understand how the BE influences RP in the connecting areas of hospitals where internal logistics takes place. Against this background, the research question addressed by this paper is stated as follows: how can we develop built environment design knowledge that supports RP in the internal logistics in hospitals? The expression *design knowledge* refers to both prescriptions and practical examples related to internal logistics of hospitals. The point of departure for addressing this question is the knowledge framework for the design of BE supportive of RP in health services in general, developed by Ransolin et al. (2022). However, that framework was derived from a literature review of studies focused on clinical units (e.g., wards, operating theatres), paying scant attention to the common hospital areas (e.g., corridors, storage areas). The activities that occur in these common areas are mostly related to internal logistics (e.g., transportation and storage of supplies, often over fairly long distances) and therefore substantially differ from those at the clinical units (e.g., direct patient care, exams, and preparation of medications). Therefore, the research aim is to apply the framework developed by Ransolin et al. (2022) to generate BE design knowledge associated with internal logistics. The BE design knowledge is new and expected to be useful to both BE and logistics designers.

The research question was empirically investigated in the areas that connect intensive care units (ICUs) to other hospital units, hereafter referred to as c-ICU areas, in a large teaching hospital from Brazil. ICUs were chosen because of their complex interactions with other hospital units (Bueno et al., 2019), demanding RP in the internal logistics. The study of the c-ICU areas and logistics gave rise to a design knowledge composed of design principles, design prescriptions, and practical examples of how the BE might support the RP of internal logistics in hospitals. The term *design prescription* refers to suggestions for action in a given circumstance to achieve an effect (Vaishnavi and Kuechler, 2015). The term *practical* *example* refers to an instantiation of the prescription in a real, specific setting. The term *principles*, as used by Ransolin et al. (2022), refers to sets of prescriptions that share similar goals, signifying a higher abstraction than prescriptions and examples.

4.2 BACKGROUND

4.2.1 Resilient performance and the built environment

In healthcare facilities, the activities that make up the service flows are not always properly understood by designers, resulting in unfit-for-purpose spaces (Lacanna et al., 2019; Rapport et al., 2020). This drawback results in a wide gap between work-as-imagined (WAI) in design and protocols and work-as-done (WAD) in practice (Borsci et al., 2018).

Resilience engineering can be used to understand this gap, providing visibility to RP that fills out the under specification of design (Hollnagel, 2012). RP arises partly from the informal self-organization of people and partly from deliberate design decisions intended to support it. This latter portion is associated with the concept of Design for Resilient Performance, defined as "the use of design principles to support integrated human, technical, and organizational adaptive capabilities" (Disconzi and Saurin, 2022). Ransolin et al. (2022) conducted a systematic literature review and proposed a knowledge framework composed of seven principles, 21 prescriptions, and 58 practical examples of BE design decisions that support RP in health services. The seven design principles are presented in Table 5.

Design principles		Descriptions
1	Designing layouts that support RP	BE configurations that improve the efficiency of operations and support users´ safety, well-being and interactions.
2	Supporting wayfinding	Support to the orientation and navigation of users across BE in health services.
3	Providing flexibility while maintaining the same functionality	BE attributes that allow adaptation, customization, and expansion, while maintaining the main purpose of spaces.
4	Providing flexibility for changing functionalities	BE attributes that allow adaptation, customization, and expansion, aiming at completely new purpose for spaces
5	Leveraging patient and family perspectives	Consideration of the perspectives of family members in the BE design.
6	Leveraging staff perspectives	Consideration of the staff perspectives in the BE design.
7	Reconciling the gap between the built environment-as-done (BEAD) and the built environment-as-imagined (BEAI)	BE design (i.e., BEAI) strongly based on the understanding of how people use the BE in reality (BEAD).

Table 5 - Principles for the design of BE supportive of RP – based on Ransolin et al. (2022).

4.2.2 Built environment and internal logistics in hospitals

Black and Miller (2008) group the activities of hospitals´ internal logistics into seven flows, related to: patients, family, providers, medication, supplies, information, and equipment. The patient flow takes a central stage, and thus all other flows should serve it, bridging organizational silos that usually exist in hospitals (Moons et al., 2019).

Logistics within hospitals is often constrained by the BE, which influences, for example, the choice of routes and transportation equipment, walking distances, and elevator use (Cubukcuoglu et al., 2021). Past studies have explored these implications mostly from the viewpoint of routing and layout. For instance, the proper location of the clinical units allied with a levelled traffic contribute to decrease congestion and transportation times among hospital areas (Cubukcuoglu et al., 2021). Further, departments' adjacency must match operational processes to avoid transportation waste - e.g., support and care units should be close to each other (Karvonen et al., 2017). There are also consequences to patient safety as long transportations contribute to complications in patient´s conditions (Ulrich and Zhu, 2007). Thus, it is important to avert constraints such as bumps on the floor, waiting for elevators, and lack of power outlets in the corridors (Ransolin et al., 2020; Ulrich and Zhu, 2007). Storage of equipment (e.g., wheelchairs, bed, connectors), and furniture (e.g., tables, chairs, storage cabinets) can also block staff and patient routes (Bayramzadeh et al., 2018; Battisto et al., 2009). Copeland and Chambers (2017) and Prugsiganont and Jensen (2019) described the efforts made by staff to navigate through obstacles and distractions related to the BE during the transportation of patients between units.

These examples indicate that the relationship between BE and internal hospital logistics is non-trivial. The understanding of these relationships can benefit from the modelling of the connections between logistics functions and BE. For this purpose, a possible approach is through using the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012). In FRAM, a function corresponds to the activities required to produce a certain outcome (Hollnagel, 2012). Ransolin et al. (2020) used the FRAM for modelling the connections between functions in an ICU (e.g., patient discharge, drug administration) and the corresponding BE requirements, considering these as preconditions for the functions. Hollnagel (2012) defines preconditions as "conditions that must be exist before a function can be carried out". The use of 3D representations of the BE and simulation of the workflows

(Halawa et al., 2020) can also support the joint modelling of BE and activities of internal logistics.

4.3 RESEARCH METHOD

4.3.1 Research design

To address the research question, we conducted a case study of how the BE influenced the RP of the internal logistics in a hospital, emphasizing the c-ICU areas. The case study approach was chosen as it offers exploratory insight into social-technical phenomena in real-world settings (Flyvbjerg, 2011). This fits the nature of this research as the relationship between the BE and hospital internal logistics is an under explored topic of socio-technical nature. Moreover, case studies set a basis for the bottom-up, inductive development of propositions – theories – that explain the patterns identified in the data (Woo et al., 2017). In this research study, these propositions correspond to the contents of the devised BE design knowledge supportive of RP in internal logistics.

The selection of a relevant case is crucial for external validity. As such, we chose a large (around 6,000 employees) public, teaching, and tertiary hospital in Southern Brazil. We focused on the interactions between a 95-bed adult ICU and other hospital units. These units encompass clinical (e.g., in-patient wards) and non-clinical areas (e.g., pharmacy). There were several logistics activities that took place across a three-building complex, which has around 223,000 square meters. This setting was expected to produce rich data, offering insight into the research question. Furthermore, the ICU had recently been installed in a newly built area, and the interactions with the other hospital units had not yet been completely designed and tested. Thus, ICU managers were interested in this study as its results could be applied to new workflows.

For internal validity, we followed established best practice of case-based research, namely: development of data collection protocols (Eisenhardt and Graebner, 2007); triangulation of data and data sources (Noor, 2008); development of a database, allowing traceability and reinterpretation of data when necessary (Flyvbjerg, 2011); use of visual representations to illustrate the contributions of the study (Eisenhardt and Graebner, 2007); and presentation of the results to the participants of the case study, to obtain their feedback (Rapport et al., 2018). The case study had two stages:

(i) Selection and characterization of the service flows and their BE: the selection of flows to be investigated was made in a meeting with the ICU administrative manager (4 years of experience at the ICU). This manager pointed out the main flows of people and supplies to and from the ICU, from the viewpoints of safety and efficiency. Then, the flows were characterized based on their most salient socio-technical characteristics such as distances, equipment, and people involved; and

(ii) Development of the BE design knowledge supportive of RP in internal logistics: this stage was concerned with the identification of instances of BE implications to internal hospital logistics, emphasizing situations that demanded RP.

4.3.2 Data collection

Data collection was carried out by the first author, who had been involved in a previous research project on BE and resilience engineering at the old ICU of the same hospital (Ransolin et al., 2020). This experience facilitated understanding the ICU processes and access to the sources of data. The hospital's ethics committee approved this research project, and hospital representatives who participated in the study provided written informed consent before being interviewed. Table 6 shows the sources of evidence used in each stage of the case study, resulting in a total of 81 hours of data collection.

Stages of the case study	**Sources of evidence**			
	Semi-structured interviews	**Non-participant observations**	**Meeting with hospital staff to discuss the final results**	**Document analysis**
1 – Selection and characterization of the service flows and their BE	**x**	**x**		**x**
2 – Development of the design knowledge supportive of RP in internal logistics	**x**	**x**	**x**	**x**
Total (hours)	**30**	**50**	**1**	**-**
	81			

Table 6 - Sources of evidence and their association with the stages of the case study.

Semi-structured interviews were carried out with 30 hospital representatives listed in Table 3. Altogether, 30 interviews were conducted, some of them in small groups either for the convenience of the interviewees or because they worked in close collaboration with each other. Thirteen interviewees were professionals from other hospital units which had relevant interactions with the ICU.

Interviewees		Duration of the interviews (min/h)
Type	**Number of interviewees and job**	
Hospital quality management staff	1 medical doctor*	120**
	1 nurse*	
	1 industrial engineer*	
Administrative staff	2 hospitality service managers*	
	3 ICU managers	360
	1 ICU pharmacy manager	60
	1 central pharmacy and warehouse manager*	60
	4 ward pharmacy manager*	120
	1 hospital dietary service manager*	90
	1 hospital cleaning manager*	150
	2 hospital clothing managers*	240
	2 hospital waste managers*	60
Engineering	1 architect*	90
	1 maintenance worker (mechanical)*	60
Clinical assistance	1 ICU medical-chief	60
	2 ICU doctors	120
	1 radiologist*	60
	1 ICU nursing-chief	60
Clients	1 patient	90**
	2 family members	
Total	**30 interviewees**	**1800 min/ 30 hours**

Table 7 - Interviewees, their jobs, and duration of the interviews. Notes: interviewees and groups marked with * are professionals from hospital units other than the ICU; interviews marked with ** occurred in groups.

Interviews were audio-recorded and two questions were asked: (1) could you give an overview of the functioning of this unit and its corresponding service flows related to the ICU? Please emphasize the role of the BE; and (2) how does the BE facilitate or hinder everyday work regarding the ICU service flows? Patients and family members were only asked to report their perceptions on the BE in the c-ICU areas.

Non-participant observations (50 hours) occurred over 32 visits to the hospital, encompassing: observation of the functions performed by frontline workers in the c-ICU areas; walkthrough sessions in which staff involved in workflows guided the main researcher through the c-ICU areas, explaining the logistics activities and the BE where they occurred; staff meetings to discuss adjustments and pending issues in the BE as the ICU had been recently installed; and one training session for the ICU-based team in charge of resuscitation in all units of the hospital – this was one of the selected workflows. Interviews and observations were discontinued when saturation was perceived to have occurred, which means that findings started being repetitive and the data collected was regarded by the researchers as sufficient for the purpose of addressing the research goals (Ritchie et al., 2003).

Document analysis involved the Brazilian regulation RDC-50 (Anvisa, 2002), which defined some BE requirements for the c-ICU areas. Moreover, a building information model (BIM) previously developed by Ransolin et al. (2020) for the same hospital, using the software *Autodesk Revit Architecture*, was consulted as it contained architectural floor plans and a 3D model of the hospital complex.

There was also a **meeting with hospital staff** (1 hour) to present the design knowledge in an online environment. The audience consisted of seven professionals from the administrative staff, engineering, and clinical assistance. All of them had been interviewed during data collection. The main researcher presented each element that formed the BE design knowledge, along with images from the hospital. Participants were asked to provide feedback on the clarity and applicability of the material presented.

4.3.3 Data analysis

Data from all sources of evidence were subject to a thematic analysis following the steps recommended by Pope et al. (2000): familiarization, identifying themes, coding, charting, and mapping and interpretation. To comply with ethics and privacy guidelines, empirical data were de-identified and saved in an online educational institution storage. For familiarization, the primary coders (NR and TAS), both experienced human factors and resilience engineering researchers, read several times the relevant regulations, the transcripts from the interviews, and notes from observations, which jointly accounted for about 15,000 words. Next, a priori structure, corresponding to the seven design principles presented in Table 5, was selected to define the initial themes.

Following, data were coded by NR and TAS independently in accordance with the initial themes. Such coding involved the triangulation of sections of text from all data capture approaches that were related to the same themes, embellishing one another.

These authors had three meetings to discuss disagreements, achieve coding consensus, and maximise rigour. For the purpose of assessing face validity, the three other authors (RCW, CTF, and FR) later reviewed the consensual coding from NR and TAS, suggesting minor adjustments. The coding process occurred according to different levels of abstraction, referred to as 1st and 2nd order coding (Figure 11). First order coding, the lowest abstraction level, was carried out deductively and involved the identification of excerpts of text associated with the seven design principles. For instance, the following remark by the manager of the resuscitation team was associated with the design principle 'supporting wayfinding': "*we have mirrors at the intersections between corridors to see when someone is coming in our direction; this helps to prevent collisions with stretchers or equipment*". These excerpts, 1st order codes, gave rise to the first and lowest level of the BE design knowledge. This level is hereafter referred to as practical examples of BE supportive of RP in internal hospital logistics. For the aforementioned excerpt, the example was worded as "install mirrors at the corridor crossings".

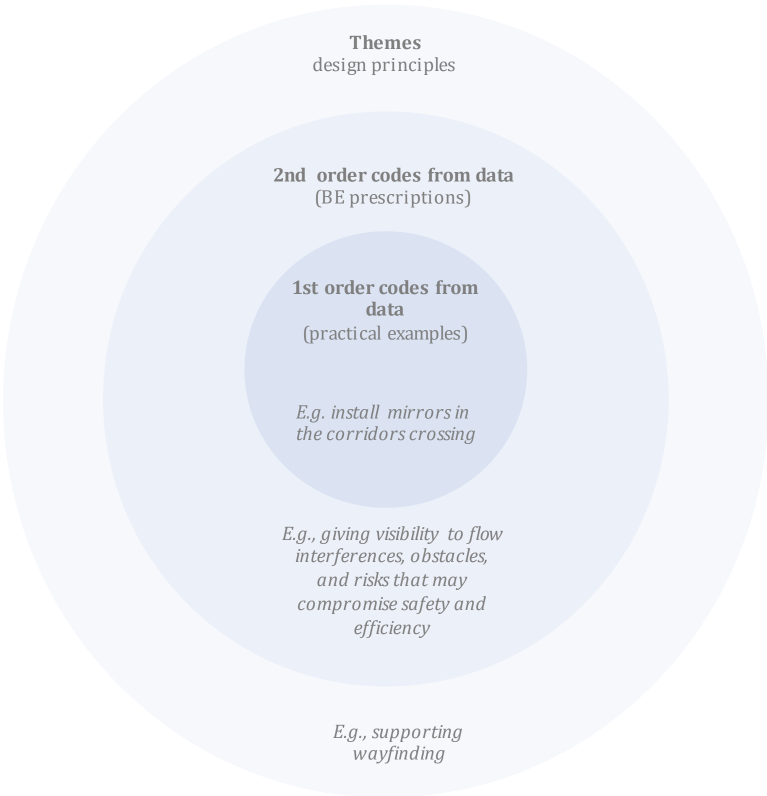

Figure 11 - Coding process.

Next, 2nd order coding was conducted inductively, giving rise to design prescriptions that encompassed several examples that were grouped according to a similar core purpose. For instance, the aforementioned example was grouped with others that were similar, to generate the prescription "giving visibility to flow interferences, obstacles, and risks that hinder safety and efficiency". The thematic analysis continued with the charting stage, which schematically represented the design knowledge. Finally, at the mapping and interpretation stage, results were discussed in light of resilience engineering and logistics theoretical background.

4.4 RESULTS

4.4.1 Selection and characterization of the service flows and their built environment

The ICU has 95 individual patient rooms arranged in 10 pods, nine of them with ten beds each and another with five beds. A standard room accommodates approximately 30 items of equipment, furniture, and materials. The ICU spreads over two floors, 6^{th} and 7^{th}, of a 7-floor building. There were around 380 employees, involving doctors (64), nurses (60), nurse technicians (190), physiotherapists (5), speech therapists (2), nutritionists (2), nutrition technicians (5), social assistants (2), pharmacists (2), and pharmacy technicians (8), pharmacy professors (3), residents (7), multi-professional residents (14), administrative staff (9), and cleaning staff (10). The average length of patient stay is seven days. Specialized and sophisticated life-supporting devices are necessary such as haemodialysis machines (14), equipment for extracorporeal membrane oxygenation for cardiovascular or pulmonary failure (3), oxygen cylinders (3), intra-aortic balloons (2), and physiotherapeutic objects (400).

The service flows that interact with the ICU were divided into two main groups, related to people and supplies. There were five flows related to people: the resuscitation team, which was physically based in the ICU but provided on-call assistance to all hospital units, patient admission, patient discharge, patient exams, and visitors (including family). As for supplies, there were six flows, involving drugs and medical supplies, sterilized materials, dietary, cleaning, clothing, and waste. The 11 flows span large horizontal and vertical distances, spread over two interconnected buildings (the new one with seven floors and the old building with 13 floors). The flows occurred mostly in the common circulation areas between hospital units (e.g., corridors, elevators, sidewalks, and roads), the warehouse elevator, as well as in the pneumatic tube system (Figures 12 and 13).

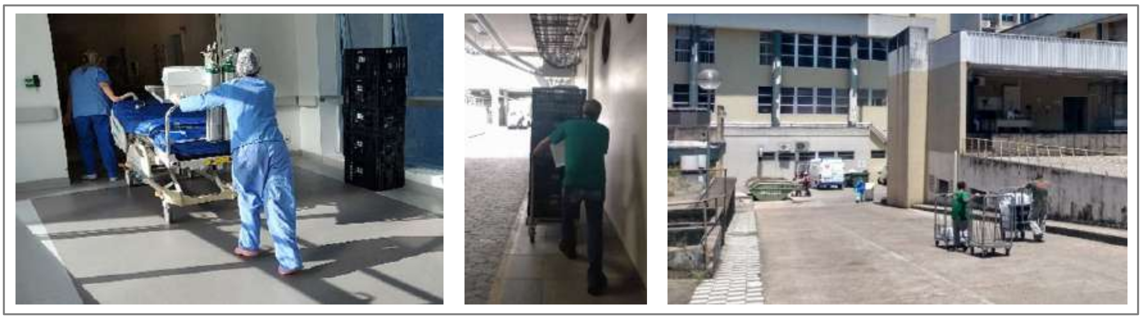

Figure 12 - Left: corridors at the entrance to the ICU; middle: sidewalks at the underground; right: roads at the underground.

The warehouse elevator is commonly used to transport supplies and medical materials, connecting hospital units (e.g., central pharmacy and warehouse, and sterilized materials centre). In turn, the pneumatic tube system (Figure 13) is composed of a network of tubes under conditions of vacuum, for the transportation of drugs, blood samples, and other small supplies between hospital units.

Figure 13 - Left: elevator that connects the main hospital warehouse to the ICU pharmacy; right: pneumatic tube and capsules for placing materials.

Table 8 and Figure 14 present the characteristics of the service flows, the related c-ICU areas, and the hospital units that interact with the ICU. The cells marked with an X indicate that there is a service flow connecting the hospital unit and the ICU.

Hospital units that interact with the ICU	**Selected service flows**											**Total**
	People					**Supplies**						
	RS	**EX**	**AD**	**DH**	**VI**	**D/M**	**DI**	**SM**	**CL**	**CH**	**WA**	
Central pharmacy and Warehouse						**X** **205m** (S:124m + C:57m + E:24m or WE:24m) **Or 24m** (PT)						1
Clothing										**X** **290m** (R:174m + C:92m + E:24m)		1
Cleaning									**X** **126m** (S:34m + C:92m + E:24m)			1
Waste management											**X** **205m** (R:205m + C: 92m + E:24m)	1
Reception desk					**X** **152m** (C:129m + E:23m)							1
	X	**X**	**X**									

Emergency department	**170m** (C:147m + E:23m)		**250m** (C:245m + E:5m)			**170m** (C:147m + E:23m)						3
Kitchen							X **270m** (C:247m + E:23m)					1
Radiology	X **285m** (C:267m + E:18m)	X **240m** (C:22m+ E:18m)										2
Laboratory		X **18m** (PT)										1
Ward	X **124m** (C)			X **124m** (C)								2
Surgical unit	X **134m** (C:126m + E:8m)		X **134m** (C:126m + E:8m)									2
Sterilized materials centre								X **54m** (C:50m + E:4m) **Or 4m** (WE/PT)				1
Ward pharmacy						X **128m** (C:116m + E:12m) **Or 12m** (PT)						1
Total	**713m**	**508m**	**304m**	**124m**	**152m**	**333m**	**270m**	**54m**	**126m**	**291m**	**205m**	-
Legend												
	Horizontal distances: Corridors (**C**); Sidewalks (**S**); Roads (**R**) **Vertical distances:** Elevators (**E**); Pneumatic Tube (**PT**); Warehouse Elevator (**WE**)											
	Patient: Resuscitation (**RS**); Exams (Radiology/Laboratory) (**EX**); Admission (**AD**); Discharge (**DH**) **Family**: family members and visitors (**VI**)											
	Supplies: Drugs and Medical Materials (**D/M**); Dietary (**DI**); Sterilized Materials (**SM**); Cleaning (**CL**); Clothing (**CH**); Waste (**WA**)											

Table 8 - Selected service flows to and from the ICU.

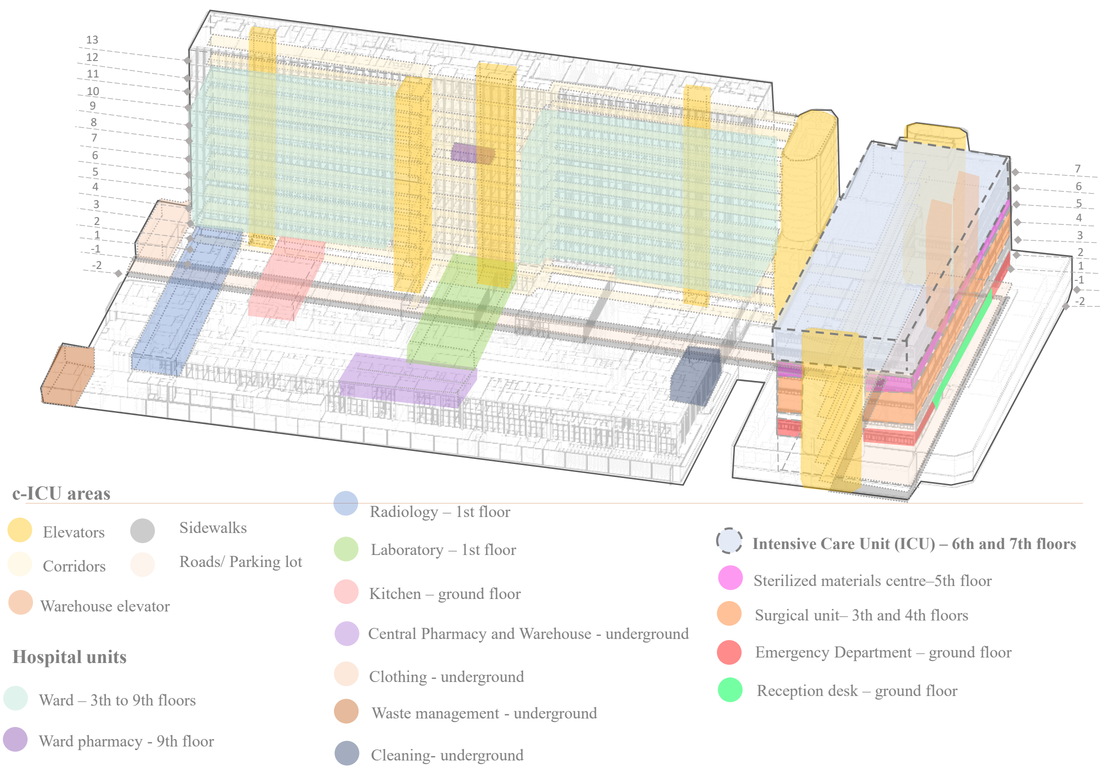

Figure 14 - Hospital units, c-ICU areas, and service flows.

The longest flow involves the transportation of clothing, accounting for approximately 290 m (266 m horizontal and 24 m vertical) between the ICU and the clothing unit. By contrast, the flow of supplying the ICU with sterilized materials is the shortest, accounting for about 54 m (50 m horizontal and 4 m vertical). The emergency department (ED) is the unit with the largest number of service flows (three) connected with the ICU, namely those related to the resuscitation team, examination and admission of patients. This makes sense as admission to the ED often precedes ICU admission.

4.4.2 Development of the BE design knowledge supportive of RP in internal logistics

In this section, seven design prescriptions and 63 examples are presented. In addition to these results, there is a supplementary material composed of photos that visually illustrate the findings. The utility of the findings was highlighted by the hospital architect who attended the meeting for the discussion of the final results. She remarked that the study *"gave visibility to the contribution of the architecture and engineering department, which is seen as of secondary importance by hospital managers; this study raises the question of whether the built environment is supportive of the expected hospital processes"*.

Note that, from Tables 9 to 15, the shadowed lines indicate the association between examples and flows - e.g., the full shadowed line below example 1 conveys that this example is applicable to all service flows. The total number of examples per service flow is provided at the bottom row of the tables. The sources of the examples are also presented, whereas I stands for interviews, O for observations, and R for regulation. Considering all 63 examples, their origin according to sources was as follows: 44% from both interviews and observations; 25% from all sources; 13% from observations; 8% from both observations and regulations; 5% only from interviews; 3% from both interviews and regulations; and 2% from regulations. As such, 80% of the examples originated from at least two sources of data, reinforcing their credibility.

The design prescription "design safe, efficient, and flexible routes between hospital units" addresses three complementary performance dimensions and includes nine examples (Table 9). Only example 1 (i.e., creating direct connections between hospital units) is applicable to all flows, while example 2 (i.e., positioning of columns should allow space for manoeuvring) is the second most applicable, being relevant to 10 out of the 11 flows. Thus, both examples 1 and 2 pose either constraints or opportunities for a wide range of logistics activities.

Although other examples (6, 7, 8, 9) are limited to one flow, they have relevant implications. To illustrate, the uptake of example 7, related to avoiding curves in the pneumatic tube, prevents blockages that otherwise could lead the tubes to stop working and delaying the delivery of drugs. These delays can trigger the need for using other drugs as replacement (i.e., a resilient action) and/or delays in the administration of drugs to patients.

Design safe, efficient, and flexible routes between hospital units											
Flows	People					Supplies					
	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
Practical examples											
1. Create direct connections between hospital units located in different buildings (e.g., walkways in all floors). This prevents inter-building transit only through the ground floor. (O)											
2. Position columns to free up space for manoeuvring of trolleys, stretchers, and other equipment. (O, I)											
3. Place workstations for professionals in the corridors in such a way that this does not compromise the minimum free width of corridors set by regulations (O, R)											
4. Adopt roofed supply transportation paths as a protection against inclement weather. (O, I)											
5. Design easy-to-use and standard device in elevators (e.g., key or card) to allow for a non-stop journey to the desired floor. This can be crucial, for example, for the resuscitation team when attending a cardiac arrest. (O, I, R)											
6. Design standardized routes for waste collection from hospital units. (O, I)											
7. Avoid curves in the pneumatic tube pipes so as not to damage nor block the load. (I)											
8. Locate origin and destination areas adjacent to each other to minimize the transportation of critical patients (e.g., place post-operative beds inside the ICU). (O, I)											
9. Review the route to the unit that requested cardiac arrest assistance before leaving the ICU. Standardized routes should not be taken for granted as they may be blocked due to changes in spaces and processes. Additionally, a nurse technician can be allocated to leave earlier and free the routes (e.g., fire doors are often heavy and difficult to handle in an emergency), and provide key cards for resuscitation team members to access all hospital environments. (O, I)											
Total of practical examples per flow											
	5	4	4	3	1	6	4	4	4	4	5

Table 9 - Practical examples associated with the BE design prescription "design safe, efficient, and flexible routes between hospital units".

The design prescription "assess the pros and cons of centralisation and decentralisation of support areas that serve several hospital units" encompasses five practical examples (10 – 14), according to Table 10. The examples most applicable (10 and 11) highlight the benefits of centralized support areas to make the best use of resources such as personal protective equipment and facilities for exams. By contrast, examples 13 and 14 highlight the benefits of decentralisation such as decentralised supporting rooms (e.g., deposits of materials and waste) to reduce movement of staff. In fact, during the meeting to discuss the final results, a nurse highlighted that both centralization and decentralization can co-exist for the same family of materials. She used the case of sterilized materials to make this point, mentioning that some of these materials can be best stored at the ICU nursing stations while others are best stored in a central room at the ICU – it depends on the pattern of demand of each instrument in each ICU.

<table>
<tr><th colspan="12">Assess the pros and cons of centralisation and decentralisation of support areas that serve several hospital units</th></tr>
<tr><th rowspan="2">Flows</th><th colspan="5">People</th><th colspan="6">Supplies</th></tr>
<tr><th>Resuscitation</th><th>Exams</th><th>Admission</th><th>Discharge</th><th>Visitors</th><th>Drugs and Medical Materials</th><th>Dietary</th><th>Sterilized Materials</th><th>Cleaning</th><th>Clothing</th><th>Waste</th></tr>
<tr><td rowspan="12">Practical examples</td><td colspan="11">10. Design supporting areas, such as clothing and exam hubs (e.g., for gowns and radiology service) that serve more than one hospital unit, avoiding replication of resources. (O, I, R)</td></tr>
<tr><td colspan="5"></td><td colspan="6"></td></tr>
<tr><td colspan="11">11. Share expensive and scarce equipment or infrastructure (e.g., tomography, defibrillators, crash carts, pharmacy) between ICUs and other hospital units. (O, I)</td></tr>
<tr><td colspan="4"></td><td></td><td></td><td></td><td></td><td colspan="3"></td></tr>
<tr><td colspan="11">12. Design decentralised supporting rooms (e.g., deposits of materials and waste) to reduce movement of staff. (O, I)</td></tr>
<tr><td colspan="5"></td><td></td><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="11">13. Design rest and green areas with stimulating colours, furniture, decoration, and art to be used by several hospital units (e.g., terraces and patios with space for mobilisation and physiotherapy). (O, I)</td></tr>
<tr><td colspan="2"></td><td></td><td></td><td></td><td colspan="6"></td></tr>
<tr><td colspan="11">14. In cases where supporting rooms are decentralised, waste collection routes might be more effectively arranged according to building plans (e.g., east-west or north-south). (I)</td></tr>
<tr><td colspan="10"></td><td></td></tr>
<tr><td colspan="11">Total of practical examples per flow</td></tr>
<tr><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>3</td><td>1</td><td>3</td><td>2</td><td>1</td><td>2</td></tr>
</table>

Table 10 - Practical examples associated with the BE design prescription "assess the pros and cons of centralisation and decentralisation of support areas that serve several hospital units".

The design prescription "give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility" encompasses 14 practical examples (15 – 28) (Table 11). Two of these examples apply to all service flows: installing mirrors in the corridor crossings to ensure the visualisation of incoming flows is important when transporting patients and over-sized equipment (example 15); and balancing the need to keep restricted access with freeing access during emergencies (example 16).

<table>
<tr><th colspan="12">Give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility</th></tr>
<tr><th rowspan="2">Flows</th><th colspan="5">People</th><th colspan="6">Supplies</th></tr>
<tr><th>Resuscitation</th><th>Exams</th><th>Admission</th><th>Discharge</th><th>Visitors</th><th>Drugs and Medical Materials</th><th>Dietary</th><th>Sterilized Materials</th><th>Cleaning</th><th>Clothing</th><th>Waste</th></tr>
</table>

Practical examples	**15.** Install mirrors in the corridors' crossings to ensure the visualization of incoming flows. (O)										
	16. Balance concerns with ease of access during emergencies (e.g.,in case of fire; the resuscitation team needs to quickly unlock doors; electronically controlled doors may hamper the access for cleaning staff) and access restrictions due to security requirements (e.g., psychiatric patients may try to escape). (O, I, R)										
	17. Design places to store dirty clothes separately from the storage of clean clothes. (O, I)										
	18. Use colours to identify laundry cage covers according to the service flow (e.g., yellow for clean clothes distribution and blue for collection of dirty clothes). (O, I)										
	19. Allocate a signalized area for parking supply carts and unloading materials near the ICU pharmacy. (O)										
	20. Include information about bed numbers on directional signs in the corridors to facilitate patient search in the ICU. (O, I)										
	21. Use dedicated elevators for patients to avoid flow interferences. (O, I, R)										
	22. Make key information on patient condition available for consultation by professionals during intra-hospital patient transportation (e.g., signal the decision on the resuscitation condition of patients on the bed). (O, I)										
	23. The doors of all rooms where large equipment is installed should be large enough or have removable panels. (O, I, R)										
	24. Provide detailed plan cuts of the pneumatic tube system, for troubleshooting (e.g., coping with stuck capsules or tube maintenance). (O, I)										
	25. Incorporate a system (e.g., doorbell/audible alarm/phone ring) to announce that the resuscitation team is arriving, to clear the way and be prepared. (O, I)										
	26. Allocate signalized place for parking one of the crash carts just outside of the ICU preventing access of external people who may need this equipment. (O, I)										
	27. Signal risks of people falling and locking out all chutes, using them for one purpose only (e.g., do not use the same chute for dirty clothes and waste collection). (I, R)										
	28. Design a parking area for the clothing cages just outside the clothing unit or in the pathway to the hospital units to be supplied. This releases space in the clothing unit and speeds up transportation. (O, I)										
	Total of practical examples per flow										
	7	**7**	**7**	**6**	**5**	**6**	**5**	**5**	**5**	**7**	**6**

Table 11 - Practical examples associated with the BE design prescription "give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility".

Another design prescription is "use visual management for the identification of spaces, resources, and processes". It is associated with seven practical examples (29 –35) as shown in Table 12. There are two examples applicable to all flows: using signage to increase awareness of changes in flows and spaces during times of crisis (29), and self-explanatory flow directions through the use of colours and symbols (30). The applicability of these examples stems from their benefits to wayfinding, which is a widely known concern in healthcare facilities. The other examples correspond to more specific visual management applications, being useful for the elimination of non-adding value activities such as rework and searching for materials, places, or people.

Use visual management for the identification of spaces, resources, and processes											
Flows	**People**					**Supplies**					
	Resuscitation	**Exams**	**Admission**	**Discharge**	**Visitors**	**Drugs and Medical Materials**	**Dietary**	**Sterilized Materials**	**Cleaning**	**Clothing**	**Waste**
Practical Examples	**29.** Use signage such as stickers and posters to increase awareness of temporary changes in flows and spaces (e.g., identification of dedicated COVID-19 patient transport elevator). (O, I)										
	30. Design self-explanatory direction signage for hospital flows and areas (e.g., use of colours and symbols), including hospital entrances and exits. (O, I, R)										
	31. Communicate the resuscitation team telephone number in corridors and other hospital common areas. (O, I)										
	32. Hang maps on the crash cart to help the resuscitation team identify the routes for each hospital unit. (O, I)										
	33. Design an intuitive numbering system to identify the hospital units. (O)										
	34. Create posters with spreadsheets detailing the routes (e.g., elevators, corridors, and rooms to access) with schedules, types, and amounts of waste to be removed. (O, I)										
	35. Tag the hamper before shipping it down to the chutes and cages. (O, I)										
	Total of practical examples per flow										
	4	**2**	**2**	**2**	**2**	**3**	**2**	**2**	**2**	**3**	**3**

Table 12 - Practical examples associated with the BE design prescription "use visual management for the identification of spaces, resources, and processes".

The design prescription "provide slack resources to cope with disruptions" is related to 10 practical examples (36 - 45), according to Table 13. Five examples (36 – 40) apply to all flows. Example 36 refers to having "no break" devices in the elevator to provide at least one hour of autonomy of elevator functioning in cases of power shortage. Example 37 concerns spatial slack in common areas in order to accommodate emergencies, possible new processes and/or subsets of patient profiles (e.g., obese). The relevance of this prescription was highlighted by the participants of the meeting in which the final results were discussed. According to the architect, changes in the hospital managerial and care processes occur in a much faster pace than changes in the BE. Thus, the BE is more often than not lagging behind the needs of caregivers, which makes it important to provide slack resources that offer alternative solutions while the BE is not adapted to the new demands.

Provide slack resources to cope with disruptions	People					Supplies					
Flows	**Resuscitation**	**Exams**	**Admission**	**Discharge**	**Visitors**	**Drugs and Medical Materials**	**Dietary**	**Sterilized Materials**	**Cleaning**	**Clothing**	**Waste**
Practical examples											
36. Provide elevators with a "no break" device, with a substantial autonomy (e.g., one hour) in the event of a power shortage. (R)	X	X	X	X	X	X	X	X	X	X	X
37. Design more spacious areas in elevators and circulations (i.e., slack of physical area) to include new or emergency processes and obese patients. (I, R)	X	X	X	X	X	X	X	X	X	X	X
38. Use partitions with drywall or other flexible technologies that allow further adaptation, if necessary. (O, I)	X	X	X	X	X	X	X	X	X	X	X
39. Design circulation areas that include manoeuvring space to large equipment. (O, I, R)	X	X	X	X	X	X	X	X	X	X	X
40. Design alternative routes in case the usual route is closed (e.g., in case of elevator maintenance). (O, I)	X	X	X	X	X	X	X	X	X	X	X
41. Design multiuse spaces that have a regular use but can serve as a warehouse of equipment and supplies during crises or in times of building transition. (O, I)			X		X	X			X	X	X
42. Provide power plugs in the corridors for equipment recharging during the transportation of critical patients. (O, I)	X	X	X	X							
43. Design backup areas for expanding ICU bed capacity during crises such as the COVID-19 pandemic. The infrastructure of these areas (e.g., oxygen and electricity supply) should be as close as possible to that of the designed ICUs. Interactions between the backup ICU and other hospital units should also be anticipated in design. (O, I)	X		X			X					
44. If the change of the patient's stretcher is unavoidable, define an area with sufficient size to carry out the change, considering two stretchers side-by-side with the teams around. This can be necessary, for example, when transferring patient from stretcher to bed in the surgical room or radiology. (O)		X	X	X							
45. Design transition spaces between hallway and industrial kitchen to accommodate lines for employees and equipment (e.g., waiting areas with seating and parking spaces). (O)							X				
Total of practical examples per flow	**7**	**7**	**9**	**7**	**6**	**7**	**6**	**5**	**6**	**6**	**6**

Table 13 - Practical examples associated with the BE design prescription "plan slack resources to cope with disruptions".

Table 14 presents six practical examples (46 – 51), related to the prescription "design for the prevention of infections and contamination". An idea underlying most examples is the reduction of interactions between flows of people and supplies. Thus, even the examples with fewer corresponding service flows (50 and 51) involve keeping people and supplies away from sources of contamination.

Design for the prevention of infections and contamination											
Flows	People					Supplies					
	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
Practical Examples											
46. Redefine flows and uses of existing areas to prevent infections and contamination (e.g., dedicated waiting rooms for patients suspected of contamination, dedicated collection and distribution routes for contaminated clothing and waste). (O, I, R)	■	■	■	■	■	■	■	■	■	■	■
47. Create only a few points of access to restricted areas, in order to reduce unwanted traffic. (O, I, R)	■	■	■	■	■	■	■	■	■	■	■
48. Place hand sanitizers in the corridors and at the entrance of the hospital units. (O, R)	■	■	■	■	■	■	■	■	■	■	■
49. Design devices to seal possible contaminated materials that need to be transported. (O, I, R)						■				■	■
50. Design dedicated routes, at least partly, (e.g., dedicated elevators) between restricted areas, such as for the transit of sterilized materials and the access to the warehouse elevator. (O, I, R)								■			
51. Design devices to prevent clothes from falling out of the cage during clothing transportation (e.g., rails). (O)										■	
Total of practical examples per flow	3	3	3	3	3	4	3	4	3	5	4

Table 14 - Practical examples associated with the BE design prescription "design for the prevention of infections and contamination".

The last design prescription is stated as "use technologies supportive of safe, efficient, and flexible service flows". The use of these technologies can demand the management of trade-offs – e.g., aural alarms to notify the arrival of the resuscitation team (60) can be noisy and hinder patient comfort. This prescription is based on 12 practical examples (52 - 63), as shown in Table 15. Examples 52 and 53 account for all flows, being related, respectively, to the use of furniture, finishing and coating materials that facilitate cleaning and disinfection activities, as well as to the installation of devices to ensure that elevators are levelled with the floors.

The technologies accounted for by the examples range widely in terms of cost, from cheap trolleys´ handles (55) to expensive flexible ICU beds (57). Thus, technologies are not equally affordable by all healthcare organizations, highlighting the point that RP can be costly. The exemplified technologies have an impact on the safety and well-being of both patients and providers. Patient safety implications are illustrated by example 56, which addresses the need to hold the doors open for teams passing. This is necessary in cases of urgencies such as transporting patients to the ICU or moving the crash cart for patients´ resuscitation.

Use technologies supportive of safe, efficient, and flexible workflows											
	People					Supplies					
Flows	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
Practical Examples	**52.** Use furniture, finishing and coating materials that facilitate cleaning and disinfection activities – e.g., furniture without roughness, surfaces with as few grooves or crevices as possible, coating materials that do not require the application of wax on the floor. (O, I, R)										
	53. Automatic levelling of all lifts with the floors. For patient lifts, the movement of the doors must be delayed. (O, R)										
	54. Prevent noise in the corridors using practices such as televisions on mute, with subtitles, and wheels of stretchers and trolleys that allow for smooth transportation flow. (I)										
	55. Put handles to easily push carts during transportation (e.g., carts of patients' meals, crashing and clothing cages). (O, I)										
	56. Design device to temporarily hold the fire door open during the team's passage in an emergency such as in a patient resuscitation call. (O, I)										
	57. Use flexible ICU beds that make it unnecessary to change to another bed/stretcher for transportation between hospital units. Such flexible beds should accommodate the attachment of equipment (e.g., monitors, infusion pumps, and oxygen cylinders) and allow procedures in the surgical centre (e.g., use of saw and perforator, tracheostomy). (O, I)										
	58. Provide handrails on at least one side wall in corridors where patients circulate, with a curved end; crash rails can also be used as handrails. (R)										
	59. Design pneumatic tube stations that easily adapt to new installations when pneumatic systems are updated. (O, I)										
	60. Call and arrival notices of the resuscitation team should not disturb other patients (e.g., using flashes in the electronic record and visual devices in points seen by teams and not by patients). (O, I)										
	61. Use cleaning machines that wash and vacuum the floor simultaneously, improving efficiency. (O, I)										
	62. Implement alerts (e.g., via cell phone) to indicate when storages of waste are full and need to be collected at the units. (I)										
	63. Provide chute or similar installations that facilitate the collection of dirty clothing from hospital units using the force of gravity. (O, I, R)										
	Total of practical examples per flow										
	7	**7**	**6**	**6**	**2**	**5**	**4**	**4**	**5**	**5**	**5**

Table 15 - Practical examples associated with the BE design prescription "use technologies supportive of safe, efficient, and flexible service flows".

4.5 DISCUSSION

Figure 15 schematically presents the BE design knowledge that addresses the research question, being composed of design principles, design prescriptions, and practical examples. In common, all principles, prescriptions, and examples, share the purpose of supporting RP. Prescriptions and examples focus on hospital internal logistics, whereas the examples indicate possible concrete design decisions or actions that translate the prescriptions into practice. Thus, the BE design knowledge accounts for actions or decisions (i.e., prescriptions and examples) to achieve an effect (i.e., RP), consonant with the recommendations of Vaishnavi and Kuechler (2015) for the development of design knowledge.

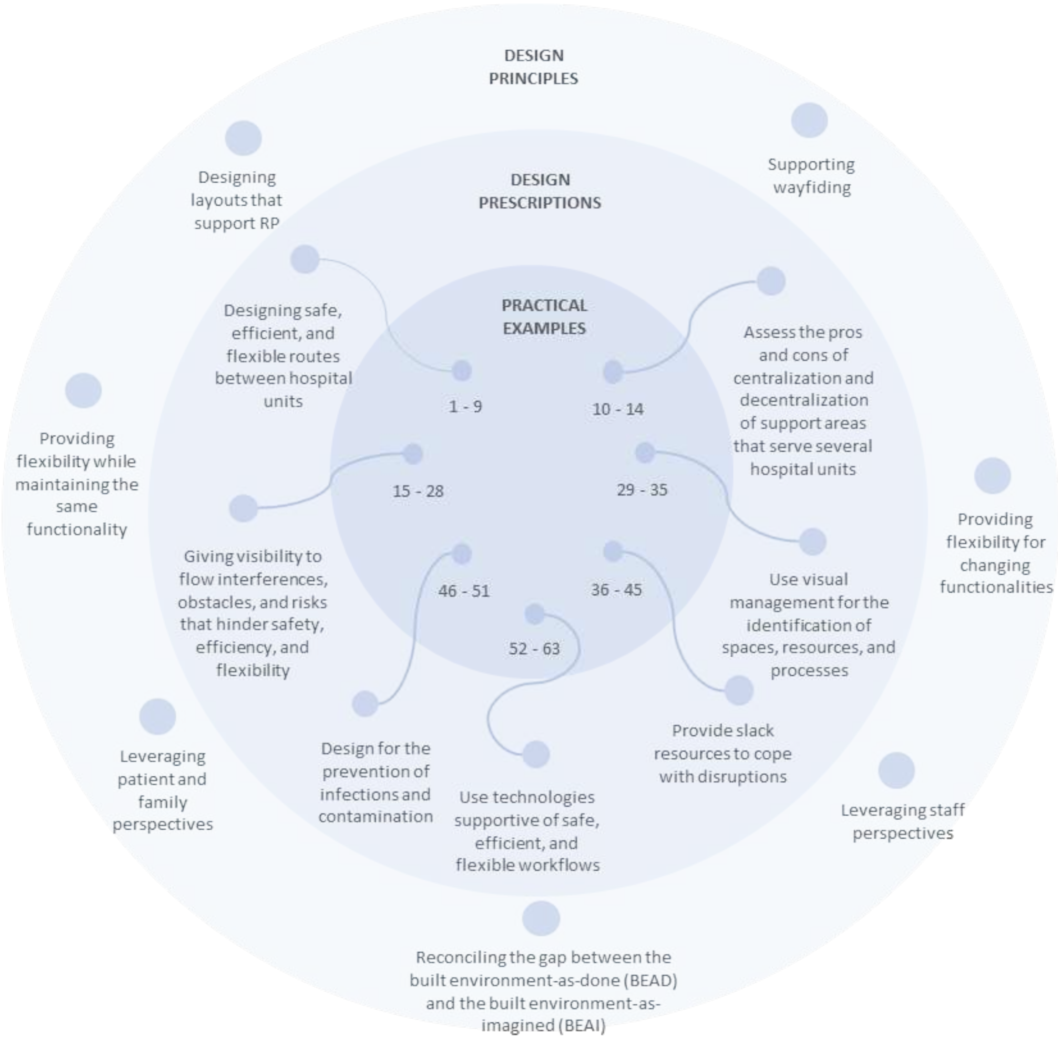

Figure 15 - Schematic representation of the BE design knowledge levels and their connections.

The design principles are more generic and underpin either all or some of the prescriptions (Kuechler and Vaishnavi, 2012) – e.g., the principle of leveraging staff perspective underlies all prescriptions. Indeed, the design principles that served as a starting point for data coding (Ransolin et al., 2022) proved to be sufficiently generic for the identification of practical examples and prescriptions of logistics relevance such as routes and centralisation and decentralisation trade-offs. Thus, this study demonstrated the applicability of the design principles to a different context, giving rise to new prescriptions and practical examples that are sources of ideas to designers.

The prescriptions are related to each other and they are context-dependent; this makes sense as RP is also context-dependent (Anderson et al., 2020). For instance, the prescription related to the use of technologies supportive of safe, efficient, and flexible workflows can contribute to the prescription for safe, efficient, and flexible routes. Moreover, the effectiveness of these prescriptions depends on contextual factors (e.g., caregivers qualified to operate the technologies, and structural constraints hindering the renovation of old buildings for the improvement of routes). There can also be conflicts between the prescriptions – e.g., designing for the prevention of infections can create closed spaces that hinder the visibility of service flows. Further, not all prescriptions can be equally affordable by different hospitals. Thus, the framework must be regarded as a source of ideas to designers rather than a template for full compliance. In fact, trade-off choices are commonplace in BE design in general (Jallow et al., 2014).

Moreover, considering that the BE characteristics are long-lasting and relatively static over time, flows constrained by the BE can work under degraded conditions for a long time. This situation offers plenty of opportunities for the rise of resilient practices developed on the spot by workers, not rarely creating new hazards (Ransolin et al., 2020). Some of these implications are implicit in earlier studies of hospital internal logistics that do not frame certain problems as BE issues (Moons et al., 2019; Cubukcuoglu et al., 2021). In fact, prior studies paid scant attention to a number of details revealed by the present work – e.g., dimensions of the corridors that make up the routes and provision of power plugs on hallways. The high level of granularity of this study is intended to resonate with both logistics and architectural designers. Decisions made by both professional groups are strongly inter-related as they share the ultimate purpose of supporting the RP of health services. These interfaces between design disciplines are frequently ill-addressed in the design process (Soliman-Junior et al., 2022). Workers are forced to fill out gaps in design at the cost of their own safety and health (Terra et al., 2023). This overuse of RP at the front-line can play out, for example, in using long and unsafe routes, as well as in exposure to contamination when sharing elevators with infected patients.

In this respect, it is worth making explicit the relationships between the BE design knowledge and the four potentials for RP. The potential of **monitoring** is logically related to the prescription on visual management as it allows people to monitor the service flows through healthcare facilities that should be as intuitive and self-explanatory as possible. In turn, the potential of **anticipating** plays out as a consequence of planning slack resources since these are usually designed to cope with anticipated disturbances.

As for the **responding** potential, it can benefit from slack resources, technologies supportive of service flows, and visibility of flow interferences. The responding assets provided by the BE manifest both in prepared responses that do not need to be activated by people (e.g., design device to temporarily hold the fire door open during the team's passage in an emergency) and responses that need human action on the spot – e.g., react to incoming traffic by looking at mirrors in the corridors' crossings. Both types of support reinforce the point that the BE poses long-term opportunities and constraints to RP (Ransolin et al., 2020). As for the **learning** potential, it can be more closely and logically related to the BE design prescription on assess the pros and cons of centralisation and decentralisation. Understanding these pros and cons will improve by learning about past experiences that prioritised either centralisation or decentralisation.

Additionally, the proposed BE design knowledge fits the concept of design for resilient performance (DfRP), defined in section 2. Disconzi and Saurin (2022) propose principles of DfRP that expand the four resilience potentials. One of these principles recommends the use of multiple perspectives in design, which is related to the previously mentioned combination of the expertise of logistics and architecture designers. Disconzi and Saurin (2022) also argue that DfRP should allow for acceptable performance even under degraded conditions. This is implicit in several practical examples, whose value to managers may only become clear under degraded conditions of hospital operation. For instance, during the COVID pandemic – arguably a prolonged degraded condition for health services - the frequency of transportation of patients to and from ICUs increased significantly (Pande et al., 2020). This revealed the value of facilities such as power plugs on hallways and designing alternative routes, which in normal times could be seen as unnecessary slack. Finally, the BE design knowledge is primarily a contribution to RP at the meso level of hospital services, where meso is the level that permeates and connects the activities of individual hospital units (micro level). Contributions to the macro level might occur if the findings of this study are confronted with the requirements set by building code regulations and standards, which currently do not pay explicit attention to RP (Øyri, 2021).

4.6 CONCLUSIONS

The research question that guided this work concerned the development of BE design knowledge supportive of RP in hospital internal logistics to and from ICUs. It was answered by the seven design principles, seven design prescriptions, and 63 practical examples that comprise the BE design knowledge shown in Figure 15. This knowledge offers a new perspective of RP in the internal logistics in hospitals, by making BE implications explicit. This is in contrast to earlier studies, where BE issues were not framed, resulting in missed details and information. Thus, the present study bridges a gap between internal logistics and architecture in the context of healthcare facilities. Relationships between the BE design knowledge and resilience theory were made explicit by discussing the findings from the viewpoints of the four resilience potentials and the principles of DfRP. This discussion positioned this research as a contribution to understanding RP at the meso level of hospital services.

Some limitations of this study must be mentioned. First, it was based on a single case study, which may restrict the generalizability of the findings, although the case study of a large hospital provided rich information. Second, the implementation of the framework knowledge for the design (or re-design) of internal hospital logistics was not addressed. Such implementation is dependent on a number of contextual factors, such as cost, product development process, and local regulations. For instance, it is possible that not all design prescriptions are equally affordable by different hospitals. Also, the effectiveness of using the design knowledge can be influenced by the level of integration with other product development approaches. Third, the interactions between the service flows were not explored in details, which is important as they share the same physical infrastructure.

This work also gave rise to several opportunities for future studies, as follows: (i) to develop similar sets of BE design knowledge for other service flows such as those related to surgical units; (ii) to identify opportunities for improvement in regulations and standards, based on the BE design knowledge; (iii) to investigate the interactions between the service flows; (iv) to assess how the knowledge is complementary to design guidelines from other areas such as operations management in hospital logistics (e.g., algorithms for the scheduling and sequencing of service flows); (v) to develop an electronic repository of good practices of applying the design knowledge, contributing to its continuous updating and expansion, besides offering an accessible source of ideas to designers; and (vi) to apply the knowledge in the design or re-design of hospital internal logistics.

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5 PAPER III – Case Study II

Based on the outcomes from the previous papers, the second case study of this thesis aimed at developing BE design knowledge supportive of RP of surgical services. The design prescriptions from Ransolin et al. (2024) were used as a point of departure to investigate the BE and corresponding workflows of perioperative and support areas in a medium-sized private teaching hospital. The focus on 'surgical services' means that the study takes a broader view rather than focusing on the operating room environment. The refined design prescriptions along with new practical examples, and their association with specific areas and workflows, composed the main findings of this study.

The paper was accepted for publication in Construction Management and Economics on 02/02/2024 after major revisions (proof of acceptance below). Findings were also presented at an international conference and will be presented at a national conference in November this year (citations below). The journal text has been formatted to fit these pages.

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Supplementary Material - Appendix K

Authorship statement - Appendix G

Presentations - Appendix H:

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Paper as accepted for publication: Appendix J

Proof of acceptance:

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01-Feb-2024

Dear Ransolin, Natália; Saurin, Tarcisio; Clay-Williams, Robyn; Formoso, Carlos; Rapport, Frances; Cartmill, John

It is a pleasure to accept your manuscript ECAM-10-2023-1063.R2, entitled "Beyond the Operating Room: Built Environment Design Knowledge Supportive of Resilient Surgical Services" in its current form for publication in Engineering, Construction and Architectural Management. Please note, no further changes can be made to your manuscript.

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Beyond the Operating Room: Built Environment Design Knowledge Supportive of Resilient Surgical Services

Natália Ransolin, Tarcisio Abreu Saurin, Robyn Clay-Williams, Carlos Torres Formoso, Frances Rapport, John Cartmill

Abstract

Surgical services are settings where resilient performance (RP) is necessary to cope with small and large variabilities as well as a wide variety of clinical procedures and surgeons' preferences. RP benefits from supportive conditions, which include an appropriate built environment (BE). However, prior studies of BE in surgical services focus on the operating room (OR) design, giving scant attention to support areas that provide resources for what happens within ORs. This study takes a broader perspective, aiming at developing BE design knowledge supportive of RP at the surgical service as a whole. To this end, seven BE design prescriptions developed in a previous work, in the context of internal logistics of hospitals, were used as a point of departure. The prescriptions were used as a data analysis framework in a case study of the surgical service of a medium-sized private hospital. The scope of the study included surgical and support areas, in addition to workflows involving patients and family members, staff, equipment, sterile instruments and materials, supplies, and waste. Data collection included document analysis, observations, interviews, and meetings with hospital staff. Results identified 60 examples of using the prescriptions, the majority of which (77%) were related to areas other than the ORs. The developed design knowledge is framed as a set of prescriptions, examples, and their association to workflows and areas, indicating where it should be applied.

Keywords: built environment, design, surgical services, resilience, hospital internal logistics.

5.1 INTRODUCTION

In hospitals, surgical services interact with a number of hospital units, such as the sterile unit, in-patient wards, the intensive care unit (ICU), pharmacy, and maintenance (Chraibi et al., 2019; Moons et al., 2019). The individual preferences of surgeons also need to be accounted for as there can be variations in preferred work organisation arrangements, team composition, and tools (Clay-Williams and Cartmill, 2023). Due to these interactions and diversity, in surgical services, as with other health services, there tends to be a gap between work-as-done (WAD), which reflects what really happens in the workplace, and work-as-imagined (WAI), corresponding to what was supposed to occur according to plans, procedures, and policies (Hollnagel, 2014). Misalignments between the WAD and the WAI can be frequent workarounds to adjust human performance to the environment – e.g., using the ceiling light to block the air-conditioning exit when the operation room is too cold for the surgeon (Rapport et al., 2020). The potential fallout of this is, to a degree, circumvented by the resilient performance (RP) of systems of care provision. RP is an emergent systems property expressed as the capacity to monitor, anticipate, respond, and learn from expected and unexpected variabilities (Hollnagel, 2017).

Although socio-technical systems such as surgical services are intrinsically resilient to some extent (otherwise they would cease to exist), work system design plays a crucial role to support RP (Wiig et al., 2020; Disconzi and Saurin, 2022). This includes the built environment (BE) design, which shapes the service flows and participants´ wellbeing, thereby influencing RP (Halawa et al., 2020; Capolongo et al., 2020; Marshall and Touzell, 2020). Earlier studies of BE in surgical services focus on the internal configuration of operating rooms (ORs), addressing issues such as clutter caused by cables (Joseph et al., 2022; Neyens et al., 2019; Taaffe et al., 2023), and layouts that hinder patient visibility, communication among team members, and the movement of materials and people (Palmer et al., 2013; Taaffe et al., 2023; Bayramzadeh et al., 2018). Ceiling-mounted booms, workstations-on-wheels, wireless devices, standardisation of the layout design across ORs, and accessible light switches and power plugs have been proposed as means to cope with some of those issues (Taaffe et al., 2023; Jurewicz et al., 2021; Watkins et al., 2011; Gurses et al., 2012).

While important, these studies neglect the flows between ORs and support areas, and the BE where those activities occur (Gurses et al., 2012; Rapport et al., 2020). The need for considering these flows is exemplified by the process of setting up ORs, as surgical supplies and staff from several spatially dispersed locations need to arrive on-time, and be of the right type and in the correct number, thus demanding synchronisation of several logistics processes (Ahmadi et al., 2019; Göras et al., 2019; Payne et al., 2012). Therefore, BE design of surgical services must be based on inputs from a wide variety of professionals, not only from those who spend most of their time inside ORs (Patkin, 2003; Bayramzadeh et al., 2018). Hence, this study hereafter defines surgical services as the broad setting of ORs and direct support areas that contribute to the functioning of this hospital unit. This perspective expands the scope of prior studies limited to ORs, and also requires the investigation of how ORs interact with support areas, encompassing the corresponding workflows that are shaped by the BE. It is also consonant with the emergent character of RP, which arises from interactions between multiple social and technical elements (Wachs et al., 2016). Earlier studies of BE in surgical services do not explicitly address resilience implications, and they are overly focused on ORs.

Against this background, the research question addressed by this paper is framed as follows: how can we develop built environment design knowledge that supports RP in the internal logistics and perioperative areas of surgical services? The expression design knowledge refers to both prescriptions and practical examples of their application in surgical services, along with the workflows and BE areas where it should be applied. Prescriptions are suggestions for action in a given circumstance to achieve an effect (Vaishnavi and Kuechler, 2015). Seven BE design prescriptions supportive of RP in the context of hospital internal logistics, devised by Ransolin et al. (2024), are used as a point of departure for investigating the research question. This choice stems from the expanded view of surgical services adopted in this paper, which gives prominence to logistics activities (e.g., movement of people and materials) to and from ORs. The research question was investigated in a case study of one surgical service in a private, medium-sized teaching hospital in Australia. Main findings correspond to the development of BE design knowledge supportive of RP in the surgical services.

5.2 BACKGROUND

5.2.1 Surgical service flows

Surgical services involve activities associated with eight main service flows (Machry et al. (2021): patient, family, surgical team, anaesthesiology team, movable equipment, supplies, sterile instruments and materials, and waste. The patient flow is the most important one, interacting multiple times with the other flows (Fredendall et al., 2009). Surgical services involve three perioperative phases from patient admission to discharge (AusHFG, 2018): (1) preoperative, including patient preparation prior to the transfer to the OR; (2) intraoperative, in which the intervention takes place; and (3) postoperative, which begins with the post anaesthesia recovery, followed by the second and third recovery stages, when the patient is ready to be transferred to a hospital inpatient unit or discharged (AusHFG, 2018).

Nurses are usually involved in the perioperative phases as they perform or support many of the service flows (Machry et al., 2021). Technologies also play a key role. For instance, equipment should be easy to move inside the OR, such as the workstation-on-wheels, and the examination machinery shared among ORs. Surgical instruments are a key supply and they are organised into trays in carts to facilitate OR setups and must be sterilised after every use. Supplies also include medical consumables (e.g., surgical drapes, gloves, syringes), and medical materials often held in consignment with the supplier up to its consumption after the surgeries (e.g., orthopaedic instruments). Additional supplies include items such as drugs, linen, and food (Moons et al., 2019). Waste flows include general waste, used consumables and their packages, and bio-medical waste, all referred to as dirty flows that should not intersect with patients or clean sterile and non-used items (Payne et al., 2012).

5.2.2 Prescriptions for the design of built environment supportive of RP

The BE design plays a key role in facilitating or hindering RP, such as shaping the flows of patients, staff, visitors, equipment, and information (Pati et al., 2008). These implications are long-lasting as the BE, at a macro-scale, is relatively static over time. However, workers commonly adapt to the constraints posed by the BE, such adaptations playing out in changes at a micro-scale such as in the positioning of furniture and work organisation (Ransolin et al., 2020).

Ransolin et al. (2022) carried out a systematic literature review on the influence of the BE on RP. The authors developed a generic structure of BE design knowledge supportive of RP in health services, resulting in seven principles, 21 prescriptions, and 58 practical examples of BE design decisions. This knowledge was used by Ransolin et al. (2024) as a data analysis framework in a case study of internal logistics in a large teaching hospital in Brazil. Logistics activities investigated in that case study included 11 service flows to and from the intensive care unit, addressing common circulation areas such as corridors and lifts. This application gave rise to seven BE design prescriptions supportive of BE in the internal logistics of hospitals. These prescriptions and their resilience rationale are presented in Table 16.

Design prescriptions (Ransolin et al., 2024)		**Resilience rationale**
1	Design safe, efficient, and flexible routes between hospital units	Resilient systems benefit from safety (otherwise they will be disrupted by accidents), efficiency (which prevents unnecessary complexity stemming from wastes and releases resources for performance adjustment), and flexibility (which provides alternative courses of action) (Hollnagel, 2009).
2	Assess the pros and cons of centralisation and decentralisation of support areas that serve several hospital units	RP includes the management of trade-offs as in the face of scarce resources is rarely possible to excel in multiple performance dimensions (Woods, 2015; Hollnagel, 2009).
3	Give visibility to flow interferences, obstacles, and risks that may compromise safety, efficiency, and flexibility	Making variations in performance visible, preferably in real-time, supports RP (Disconzi and Saurin, 2022) as it is about coping with both expected and unexpected conditions.
4	Use visual management for the identification of spaces, resources, and processes	The functioning of complex socio-technical systems should be intuitive for their users, supporting quick and accurate decision-making in face of variabilities (Clegg, 2000; Galsworth, 2017).
5	Provide slack resources to cope with disruptions	Slack resources are defined by Bourgeois (1981) as a cushion of actual or potential resources which allows an organisation to adapt successfully to internal pressures for adjustment or to external pressures for change in policy. Slack resources can take many forms such as financial reserves, extra space, surplus of materials, workers on standby, redundant equipment, and generous time margins, among others (Saurin and Werle, 2017). Such resources make processes loosely-coupled, absorbing variabilities and buying time for RP.
6	Design for the prevention of infections and contamination	All hospital users must be safe against existent and new epidemiological hazards arising from the local context. This is a dimension of safety, which is important for RP as mentioned in the aforementioned rationale for prescription 1.
7	Use technologies supportive of safe, efficient, and flexible workflows	Technologies amplify physical and cognitive human capabilities, therefore expanding opportunities for RP, although they may create new drawbacks if their design does not account for WAD (Barrett, 2022).

Table 16 - Prescriptions for the design of BE supportive of RP in the internal logistics of hospitals and their resilience rationale.

Although these prescriptions were not originally conceived for surgical services, extant literature suggests that they are applicable to that context. Firstly, the prescription of designing safe, efficient, and flexible routes between hospital units also applies to routes within surgical services. For instance, patient handovers between perioperative phases benefit from short and unobstructed routes (Rapport et al., 2020; Abraham et al., 2023). Regarding the second prescription, the issue of trade-offs between centralised and decentralised support areas also applies to such areas located within surgical services – e.g., nursing stations and storage rooms may (or not) be centralised serving all operating rooms (Reiling et al., 2008; Ahmadi et al., 2019). The third prescription, related to the visibility of flow interferences, obstacles, and risks, is applicable, for instance, by defining visual boundaries between non-sterile and sterile areas within a surgical service (Rapport et al., 2020). The fourth prescription, concerned with visual management for the identification of spaces, resources and processes, is relevant, for example, for the indication of the need for wearing gowns before entering the intraoperative area (Chraibi et al., 2019). The fifth prescription can be illustrated by the need for an operating room reserved for urgent, unscheduled surgeries (Ahmadi et al., 2019). The sixth prescription, related to the prevention of infections and contamination, is crucial as patients are particularly vulnerable to contamination during a surgery, and part of these risks can be reduced by limiting the transit of people and materials to and from the operating room (Neyens et al., 2019; Halawa et al., 2020; Ahmadi et al., 2019). The seventh prescription, which addresses technologies supportive of workflows, can be illustrated by the use of equipment of size and shape that do not hinder patient visibility and access by the clinicians (Pati et al., 2008; Moore et al., 2010). Despite the applicability of the prescriptions, this does not mean that they suffice to surgical services. There is a need for a systematic approach for translating them to the surgical context, offering implementation examples and identifying the affected workflows.

5.3 RESEARCH METHOD

5.3.1 Research design

The case study research strategy was chosen, as it enables exploration of social-technical phenomena in real-world settings (Flyvbjerg, 2011). This is aligned with the research question as it is concerned with BE supportive of RP, which is a topic of socio-technical nature. Further, the development of BE design knowledge requires an understanding of the functioning of surgical services, which are complex settings that benefit from the holistic case study approach.

The case study was conducted in a hospital that carries out a broad range of surgical procedures, encompassing a wide diversity of surgical service flows, offering a suitable context for this study. The setting was a medium-sized private teaching hospital servicing a high socio-economic population in a metropolitan area of New South Wales (NSW), Australia. The complex consists of a 5-floor building that opened in 2010 with around 22,000 square meters. It comprises 144 beds, four inpatient wards, 13 ORs within the surgical service, two cardiac and angiogram suites, two endoscopy rooms and 20 ICU beds, and the provision of oncology, chemotherapy, radiotherapy, imaging, and pharmacy services. The surgical service is located on the first floor of the hospital. This unit facilitates the perioperative phases of surgery, mostly for patients scheduled under elective interventions. A detailed description of the surgical service, including flows and BE, is presented in section 4.2.

Established best practices of case-based research were adopted, including: development of data collection protocols (Eisenhardt and Graebner, 2007); triangulation of data and data sources (Noor, 2008); development of a database, allowing traceability and reinterpretation of data when necessary (Flyvbjerg, 2011); and the use of visual representations to illustrate the contributions of the study (Eisenhardt and Graebner, 2007). This case study had two major stages:

(i) Characterisation of the surgical service and its BE. This started with the selection of surgical service flows, in consultation with an experienced gastroenterological surgeon who has been engaged by the design facility since before the current building construction in 2007. The characterisation of the service was based on the four sub-systems of socio-technical systems defined by Hendrick and Kleiner (2001), namely social, technical, work organisation, and external environment. The BE was characterised by the description of the floor plans and analyses of perioperative phases, areas, and surgical service flows; and

(ii) Analysis of the surgical service in light of the prescriptions presented in Section 2.2. Such analysis made it possible to adapt the prescriptions to the reality of surgical services, also giving rise to several ways, referred to as practical examples, of translating the prescriptions into practice. It also shed light on the interactions between BE, workflows, and RP, highlighting the importance of considering the surgical service as a whole, rather than overemphasising the internal configuration of the ORs.

5.3.2 Data collection

Data collection was conducted by the first author (NR) after the study protocol was approved by the Macquarie University Human Research Ethics Committee (Reference number: 520221248843909). Data were obtained directly from the users of the spaces, including administrative, supporting, and clinical staff members. Secondary data were also collected from documentary regulations for the construction of healthcare facilities in NSW and analyses of floor plans. The total hours of data collection and their distribution according to the sources of evidence are indicated in Table 17. Firstly, meetings with hospital staff helped to identify interviewees, and define flows and areas from which data would be collected. Then, a first round of observations was conducted before interviews and additional observations were scheduled with staff members. Data collection was discontinued when saturation reached, meaning that findings became repetitive, and the researcher regarded the data collected up to that point as sufficient to address the research goal (Ritchie et al., 2003).

Data collection	Sources of evidence			
	Document analysis	Non-participant observations	Semi-structured interviews	Meetings with hospital staff
Hours	**-**	**30**	**16**	**6**
Total (hours)	**52**			

Table 17 - Data collection hours distribution according to the sources of evidence.

Documentary regulations analysis involved reading guidelines and regulations for planning, designing, and constructing healthcare facilities in NSW, particularly in: Building Code of Australia; the Australasian Health Facility Guidelines, which are followed by health planning units and standard components; the Guide of Wayfinding for Healthcare Facilities, the Health Facility Planning Process guideline, and the Health and the Arts Framework, from the NSW Health; the guidelines regarding managing, planning and design of the perioperative environments, including Postanaesthesia Care Unit (PACU), from the Australian College of Perioperative Nurses; and the Summary of the Australian Guidelines for the Prevention and Control of Infection in Healthcare, from the National Health and Medical Research Council. The regulations and guidelines documents comprise 1240 pages. The architectural floor plans of the hospital were also obtained and used for linking surgical service flows with the BE features.

Thirty (30) hours of **non-participant observations** were conducted across 14 visits to the setting. The researcher observed staff members during daily work (e.g., setup of the ORs, and stocking supplies) in the different perioperative phases and their interaction with the BE across service areas. Observations included flows related to surgeries using different technologies (e.g., robotic), which had different BE implications. During these visits, data were collected via field notes, recordings, and photos.

Sixteen (16) hours of **semi-structured interviews** were conducted with 18 hospital staff members from administrative, supporting, and clinical roles (Table 3). Due to the focus of the study on the surgical service, 10 participants were purposively selected from that unit for interview. Moreover, there were eight interviewees from other hospital units that played a supportive role in the daily functioning of the surgical service, such as logistics activities and patient transportation inter hospital units. Following consent by participants, interviews were audio-recorded. Demographic information such as profession, years of experience, and position at the hospital was collected. The interviews were structured around three guiding open questions: could you give an overview of your daily work? How does the BE facilitate or hinder your everyday work? Please illustrate these implications with a situation experienced by you or a colleague. Interviews were carried out in-person and lasted from 30 to 95 minutes (53 minutes on average), totalling 16 hours of recordings.

Interviewees		**Duration of the interviews (min/h)**
Type	**Number of interviewees and hospital position**	
Administrative staff	1 nurse unit manager	30
	1 ward nurse unit manager*	30
	1 strategic manager	30
	1 theatre floor manager	45
	1 prosthesis coordinator*	45
	1 supply chain manager*	70
	1 associate director of hospital operations*	60
Supporting staff	1 sterile unit manager*	60
	1 supply chain operator (store person)*	60
	1 design team leader - company representative	60
	1 coordinator of patient transportation*	45
	1 environmental services manager*	30
Clinical staff	1 surgeon	60
	1 assistant surgeon	40
	1 anaesthetist	95
	1 nurse (intraoperative: scout/scrub)	50
	1 registered nurse (intraoperative: scout/scrub)	70
	1 nurse (pre and postoperative services)	75
Total	**18 interviewees**	**955 min/ 16 hours**

Table 18 - Interviewees, hospital positions, and duration of the interviews. Notes: * refers to professionals from hospital units other than the surgical service.

5.3.3 Data analysis

Data were subjected to a thematic analysis following the steps recommended by Pope et al. (2000): familiarisation, identifying themes, coding, charting, and mapping and interpretation. Familiarisation was concerned with the multiple readings of primary and secondary data - i.e., transcripts of interviews and regulations. Field notes and transcripts of interviews accounted for approximately 12,000 words. The themes for analysis were the design prescriptions in section 2.2. Coding involved a deductive process of identification of excerpts of text from empirical data and regulations associated with design prescriptions. This stage gave rise to practical examples that were schematically represented in Tables according to the prescriptions in the charting stage. Finally, results were discussed in light of extant literature at the mapping and interpretation stage.

5.4 RESULTS

5.4.1 Characterisation of the surgical services and its BE

Data from the case study were organised into the four sub-systems that form a socio-technical system (Table 4).

Characteristics of the surgical services	

Social	• Over 300 professionals work in the surgical service, either on a full time or casual scheme, with an average of 6 years of experience in the setting. Staff members are divided into the following categories:
	  ◦ Administrative: nurse unit managers; strategic manager; theatre floor manager; and receptionists;
	  ◦ Supporting: maintenance; store persons; surgical sales representatives; pathology courier; orderlies; and cleaners;
	  ◦ Clinical: surgeons; assistant surgeons; medical students and residents; anaesthetist; assistant anaesthetist; anaesthetist nurse; nurses (scout/scrub); and assistant nurses.
	• Patient and visitors such as family members.

Technical	• The surgical service, composed of 13 ORs, is located (Fig. 1) on the first level of a 5-floor hospital building, occupying approximately 3,170 m²;
	• Imaging devices shared between the ORs when necessary, e.g., X-rays, ultrasound, and scopes. Fixed equipment includes robots and Heart-Lung machines for cardiovascular procedures. ORs have ceiling-mounted booms with flexible arms to connect with screens, surgical lights, and power plugs;
	• Sterile instruments and materials compose the surgical trays and are set up a day before the operation organised in surgical case carts next to the corresponding OR. The surgical cases can also be assembled by shelved trolleys that share items for multiple surgeries.
	  ◦ Single use instruments and implantables such as joint replacements and intestinal staplers;
	  ◦ Instruments include forceps, scissors, and retractors, varying depending on surgeons' preferences;
	  ◦ Materials include drapes, gloves, syringes, orthopaedic instruments;
	• Supplies encompass non-sterile materials and instruments, drugs such as pain reliefs and anaesthetics, linen, food, cleaning products, hand sanitisers and soaps.

Work organisation	• Surgery specialties range from general, gastroenterology, gynaecologic, ophthalmic, cardiovascular, spinal, neuro, sports medicine, and orthopaedics; • Most surgeries are for day surgery patients – i.e., out-patients who spend one day in the services; • The service is open from 7 am to 6 pm on weekdays. A stand-by team is on call for emergency surgeries after working hours and weekends. Support staff work after 6 pm in activities such as maintenance and cleaning. Some nurses work after hours to organise the surgical case carts for the next-day surgeries; • The main service flows are those of patients and family members, staff, equipment, sterile instruments and materials, supplies, and waste.
External environment	• Several hospital units interact with the surgical service, involving: sterile unit, pathology providers, warehouse, central kitchen, pharmacy, environmental services, wards, and ICU.

Table 19 - Characterisation of the surgical service according to the socio-technical sub-systems.

5.4.2 Surgical services areas and flows

Figure 16 presents the floor plan of the surgical service. From the total floor area (3,167 m²), 39% (1,238 m²) corresponds to the perioperative areas, while 61 % (1,929 m²) is occupied by the support areas. At the bottom, Figure 16 illustrates the spaces in more detail, distributed according to different levels of access restriction and the representation of service flows.

The patient flow starts in first stage of the preoperative phase, in a waiting area for admission with 27 seats. After admission, the patient is referred to the second preoperative phase, in which there are 14 patient bays, also known as holding bays, where the patient is prepared for surgery. In this phase, the nursing staff checks the patient against allergies and health conditions, the consent form is signed, and the anaesthetist and the surgeon interact with the patient. The patient bay accommodates a bed, wheelchair, space to change into a theatre gown, and chairs for family members. When authorized by the surgical team, the patient is transferred to the third stage of the preoperative phase, corresponding to one of the 11 induction rooms, also known as anaesthetic bays. In this room, the patient is prepared for anaesthesia (e.g., insertion of the cannula and sometimes drugs for pain or anxiety relief) while the OR is being cleaned from the previous surgery. Patients are anaesthetised only when inside the OR.

Once the OR is ready for surgery, the patient flow advances to the intraoperative phase. When the surgical procedure is completed, the patient is transferred to the Postanaesthesia Care Unit (PACU), marking the start of the postoperative phase. In this unit, nurses observe and monitor the patient, which is made easier by a layout with 13 open-plan bays. In some cases, a patient will be taken to the ICU as a planned post-operative admission or because of some unexpected event during surgery. The ICU is on the same floor as the PACU and ORs. PACU patients receive surgeon visits, in which the discharge for the following phases is authorised. The patient must be awake before moving to the next recovery stage in a space that has nine open-plan bays. After being ready to move to the next step, the patient goes to the final recovery stage, in a discharge lounge where there are 16 chairs with small tables for quick meals for day surgery patients.

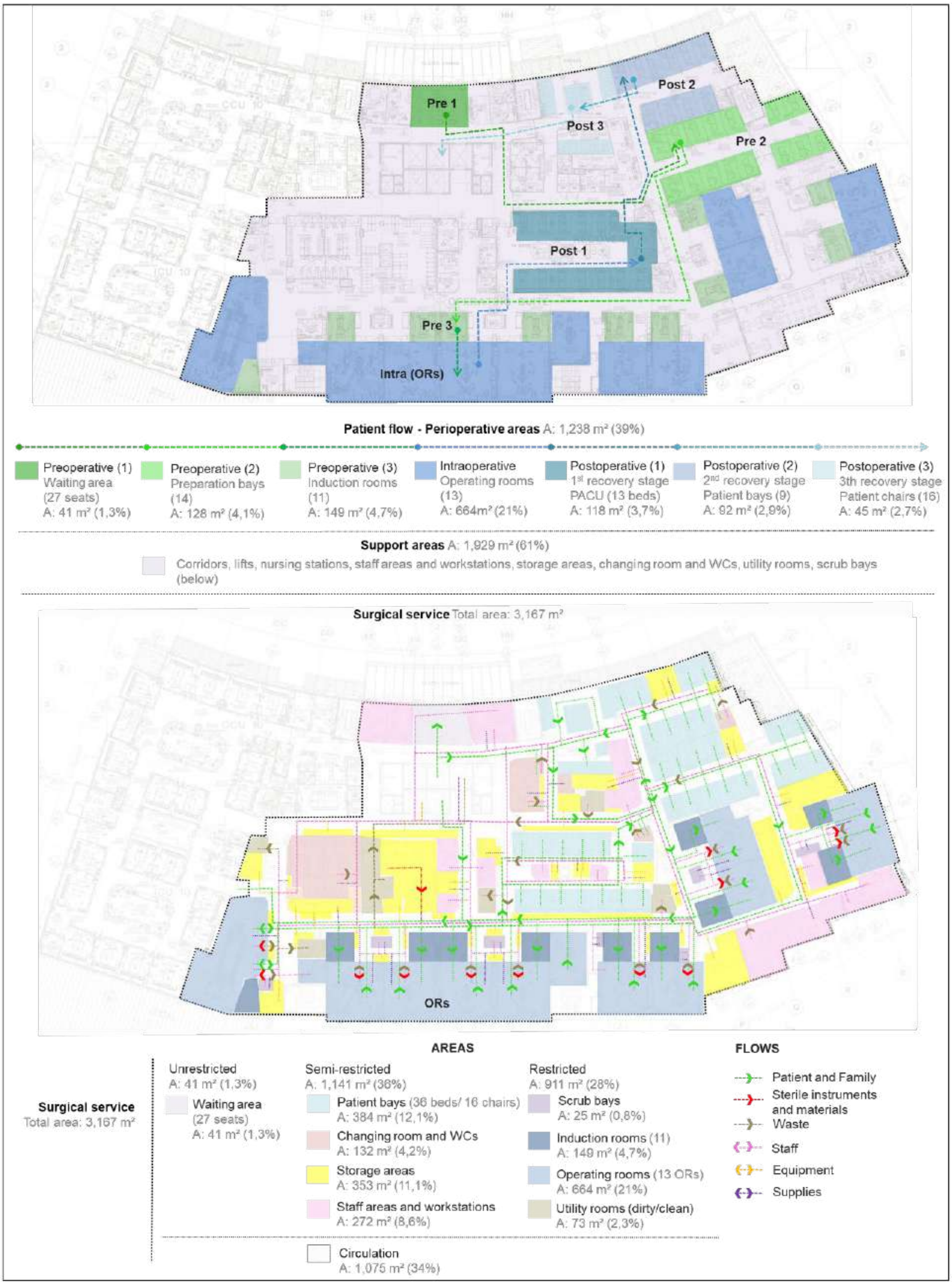

Figure 16 - On the top: perioperative and support areas, the arrows representing patient flow. At the bottom: diagrams of areas, access restrictions, and flows.

The surgical service´s floor is divided into three zones, namely: unrestricted access, semi-restricted access, and restricted access (AusHFG, 2018). Unrestricted zones (e.g., reception desk) accommodate staff, visitors, and patients. Authorized people can access semi-restricted zones (e.g., holding bays), usually wearing perioperative attire. Restricted zones (e.g., ORs) are only accessed by authorised people who must wear perioperative attire. Service flows can be unidirectional or bidirectional. Flows of sterile instruments, materials, and waste are unidirectional to avoid contamination. Sterile items are transported directly from the sterile unit, using dedicated lifts. The flows of supplies, equipment, and staff are bidirectional, as they travel along all spaces to support care delivery during the perioperative and supporting phases.

Contamination risks also exist in the flow of waste, which are contained to be transported to the waste room. After each surgery, the ORs receive a general cleaning by nurses and orderlies, focusing on the sterile field around the patient, mopping the floors, and removing the garbage. Reusable items are transported to the clean utility room for an additional cleaning and then sent to the waste room in which dedicated lifts move them to the sterile unit for reprocessing. Furthermore, cleaners undertake a terminal cleaning everyday after the last surgery in the ORs. The emergency OR takes priority over the other ORs for cleaning. Like the terminal OR cleaning, every long-lasting support activity is performed at night to avoid disruptions. For instance, during the night, the nurses organise and arrange the equipment for the following day´s operations on clearly labelled case carts corresponding to the next day's surgeries. Most surgical specialties are allocated to the same OR to facilitate the setup, which also considers surgeons preferences.

Supplies such as linen and food are provided by hospital housekeepers daily. Scrub jackets, shirts, and pants are restocked in the changing rooms, according to the capacity of the shelves; sheets and blankets are provided to storage areas to be shared between pre and postoperative areas. Food is delivered to the kitchen of the staff room and nursing stations for patients in the postoperative phase.

5.4.3 BE design knowledge supportive of RP in surgical services

This section presents 60 practical examples of applying the prescriptions to surgical services (see Tables 20 to 26). In addition, there is a supplementary material composed of photos that visually illustrate the findings (Appendix E). Some of the prescriptions were reworded to clarify their focus on a specific hospital unit, namely surgical services. The examples are ordered according to their frequency of association with the areas and service flows. This association is highlighted through shadowed lines below each example; associations with areas are represented in pink, and with flows in blue. The total count of examples per areas and flows is shown at the bottom of each table. The sources of the examples are denoted within parentheses, with 'I' signifying interviews, 'O' observations, and 'R' regulatory sources. The distribution of the examples according to their sources was: all sources (45%), from both interviews and regulations (22%), both interviews and observations (15%), exclusively from regulations (10%), from both observations and regulations (7%), and solely interviews (1%). This variety reinforces the importance of using multiple sources of data.

The prescription "design safe, efficient, and flexible routes between perioperative phases" (Table 20) encompasses six examples. Example 1 is applicable to most areas and flows, conveying that the BE design can mitigate conflicts between flows. As mentioned by one nurse interviewed, staff do not realise that patients should not be exposed to certain flows: "*we are so desensitized from all of this that people* tend *to forget that patients shouldn't be seeing what we're showing them - such as dirty bins"* (nurse unit manager). In turn, example 6, although less applicable, is nonetheless relevant for prioritising patient care and well-being in patient transfer among perioperative phases.

Design safe, efficient, and flexible routes between perioperative phases										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**1.** Ensure the separation between patient and supporting flows, which can be studied based on mock-ups. This can bring benefits such as preventing patients from seeing dirty bins and trolleys where they are crossing. (I, R)									
	2. Comply with corridor width requirement for clinical areas. Corridors should be wider enough to fit ICU beds that are larger than regular ward beds. Strategies for coping with narrow corridors can include passing bays, accommodating equipment in in-built niches, and prioritization of corridors for certain flows. (I, R)									
	3. Dimensions of doorways should fit large equipment, such as bariatric patient stretchers, to avoid damaging or patient handling to a smaller stretcher. (I, R)									
	4. Pre and postoperative areas should have separate accesses. Patients, sterile instruments and materials, and waste flows should be unidirectional, avoiding return to sterile and restricted areas. E.g., an intubated patient cannot share the corridor with a patient fully awake as it can									

	create anxiety. Thus, patient flow can be a 'circuit' design to enable optimization between these areas. (O, I , R)									
	5. Ensure a smooth transition (e.g., no bumps or irregularities) between different floor finishes. (R)									
	6. Ease of transfer and access among perioperative phases, using back-of-house corridors. PACU and ICU should be close to ORs in order ensure quick patient transfer. (O, I, R)									
	Total of practical examples per areas/flows									
	4	**1**	**4**	**6**	**6**	**1**	**3**	**2**	**3**	**2**

Table 20 – Practical examples associated with the design prescription "design safe, efficient, and flexible routes between perioperative phases".

Table 21 presents twelve examples (7- 18) associated with the prescription "assess the pros and cons of centralisation and the decentralisation of resources". The most applicable example (7) involves the trade-offs between centralisation and decentralisation of storage areas. Centralized storage is advocated for drugs and general items shared among perioperative phases, while decentralization is recommended for items specific to surgery specialty. Grouping ORs based on surgical specialties also facilitates resource-sharing among them. Resource-sharing can also be enabled by clustering similar-purpose areas such as surgical and critical care units (9, 10, 11, 12). The least applicable example (18) is the need for decentralised staff amenities such as toilets and spaces for storing personal belongings. This reduces walking distances.

Assess the pros and cons of centralisation and the decentralisation of resources										
Areas					**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**7.** There can be a centralised storage for general items shared among perioperative phases and decentralised storage areas for specific surgical items. Drugs with a higher risk of misuse must be stored in a locked cabinet shared among the ORs, allowing control and ready access nurses. In this case, clustering ORs according to surgical specialties facilitates sharing resources and ready access to decentralised storage areas. Some ORs can have doors linked to storage rooms. (I , R)									
	8. Consider the pros and cons of single corridor versus a racetrack model. The first involves sharing the same corridor by all flows and phases. The width should fit the storage of case carts, equipment, and the passageway of at least two flows in different directions. In the second solution, dirty and clean flows are separated through dedicated corridors, preventing patients from crossing equipment, waste, and contaminated instruments. (O, I ,R)									
	9. Functional links are necessary between the surgical services and the ICU, interventional angiography, sterile unit, pathology unit, blood bank, imaging centre, and hospital wards. Thus, hospital units with similar procedures can have a central storage of resources to avoid									

duplication. For example, ORs performing angiography and neuro surgeries should be close to the ICU, as cardiac arrest cart and drugs can be shared. (I, R)									
10. Cluster pre and postoperative bays to promote shared use of the spaces as admissions decrease along the day – e.g., the same bays and chairs can be used by patients and family members in both phases. Support areas of these phases such as storage, utility rooms, and toilets can also be shared. (O, I, R).									
11. Place shared resources in the boundary area between the spaces sharing the same resources, with doors for both sides – e.g., a drug storage area between the perioperative phases, allowing access from pharmacy workers without the need to scrub. Similarly, if specimens and blood samples are stored in a semi-restricted area, the pathology courier does not need to scrub when collecting them. (O, I)									
12. Design mirror-reverse OR layout allows the sharing of resources such as supplies, staff, and circulation spaces. However, a single-handling layout might be more intuitive for staff as all ORs have the same orientation (I, R)									
13. If close to each other, some services can share preoperative spaces – e.g., interventional angiography, and imaging centre. Access from adjacent units should be intuitive – e.g., surgical team should know the mechanism to open ICU doors when transporting the patient from OR. An emergency OR can have internal doors to the ICU to shorten patient flow. (O, I, R)									
14. Pre and postoperative areas should be designed as open plans to facilitate patient observation from a central nursing station, with shared workstation-on-wheels in between bays. Consideration should be given to meals and refreshments served only for postoperative patients, thus requiring an isolated area to avoid odour spread to fasting preoperative or PACU patients. (O, I)									
15. The method chosen for surgical items delivery affects the design of storage rooms – e.g., if 'just-in- time' deliveries require less storage space, despite a higher frequency of flow of store persons to fill the shelves. A solution to store more items is the mobile racking that creates space for circulation by moving a wheel. (O, R)									
16. The induction room should be close to the OR to allow the anaesthesia preparation of the following patient. The number of preoperative bays can be reduced when induction rooms are provided. (O, I R)									
17. If centralised, scrub bays can be shared between up to two ORs. Similarly, induction rooms can be shared and coordinated with OR scheduling. Imaging devices and anaesthetic machines can also be shared across the ORs or set in the OR for the same type of surgeries, avoiding rework and duplication of resources. (O, I)									
18. Provide toilets near the staff room/kitchen area, reducing walking distances to the changing rooms. Spaces to store staff belongings, such as dry snacks, could also be provided. (O, I , R)									
Total of practical examples per areas/flows									
6	**3**	**5**	**10**	**7**	**7**	**5**	**7**	**4**	**2**

Table 21 - Practical examples associated with the design prescription "assess the pros and cons of centralisation and the decentralisation of resources".

The prescription "give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility" (Table 22) is comprised of seven examples (19 – 25). Example 19 applies to all flows due to its relevance for security and traffic management. Visual demarcation on the floors and signage are suggested to separate dirty item from clean item flows (20). This prescription also emphasizes safe and uncluttered spaces by removing obstacles such as cable cluttering and improper equipment storage (21, 22, 23). Patient safety and well-being are also highlighted, benefiting from central workstations for ease of patient monitoring, and colour schemes (24, 25). The least applicable example (25) is related to prioritizing patient flows in support areas and optimizing staff schedules to prevent congestion.

Give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**19.** Reduce and monitor the entrances and exits to the surgical services. Unauthorised access creates operational and security risks such as contamination of sterile areas or theft of drugs. Clear views of these points allow surveillance from the reception desk. Demarcating ‘rings of security’ helps to monitor traffic, which can be aligned with the established area restrictions. (O, R)									
	20. Prevent interactions between dirty and clean flows. Visual demarcation can be useful for that purpose such as lines or colours on the floor and walls to indicate uses such as equipment storage. (O, I, R)									
	21. Avoid clutter as it can create obstacles and risks of slips, trips, and falls. Providing power plugs evenly distributed to reduce the use of extension leads and cables on the floor. Cableless and ceiling-mounted equipment help to prevent slips and falls. In PACU, emergency equipment must be organised and within a reachable distance – e.g., suction, oxygen, emergency basket above with airway adjuncts, and hand sanitiser. (O, I, R)									
	22. Storage spaces should keep doors open to avoid parking the trolley at the doorway to hold. Storage rooms should ideally fit two people simultaneously – e.g., a store person filling the shelves and a nurse picking up an urgent item – with the trolley inside. (O, I, R)									
	23. Avoid place heavy items on top shelves, as they are more likely to fall. Instead, a medium-height shelf with enough stability should be used for those items, as bottom shelves can also cause injury when bending. (O, I)									
	24. The anaesthetist workstation and surgeon should be positioned near the operating table for a visual connection with the patient. Patient physical and visual access during surgery can be provided by movable steps and an operating table with detachable pieces - e.g., arms and legs. Consideration should be given to the colour of TV screens, as it can change organs' colours, and for wall painting that may alter the observer's perception of patient skin tones. (O, I, R)									
	25. Patient flows must always be prioritised in corridors and lifts. Signage for dedicated use is needed during busy surgery days for staff/patient transportation. Levelling the use of changing rooms to avoid peak times is a strategy for smooth flows. (O, I)									
	Total of practical examples per areas/flows									
	2	**3**	**3**	**6**	**4**	**6**	**4**	**4**	**4**	**2**

Table 22 - Practical examples associated with the design prescription "give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility".

Table 23 relates to the prescription "use visual management for the identification of spaces, resources, and processes". It is illustrated by five examples (26 – 30). The most applicable example (26) suggests using preference cards. These cards present instructions detailing the equipment, supplies, sterile instruments, and OR setup for a specific procedure according to surgeon´s preferences (Figure 17, left). Clear wayfinding is also highlighted and includes identifying room usage and directions for users through disclosing information progressively instead of providing all directions at once and at a single point (27, 28). Example 29 involves employing kanban cards that allow an intuitive monitoring of inventory levels of supplies. Moreover, storage and replenishment of surgical items can be supported by labels on the shelves, displaying diagrams and pictures to inform staff of where each item should be placed (Figure 17 - right). The least applicable example (30) refers to safety considerations by placing signage to indicate the use of lasers and x-rays.

Figure 17 - Left and middle: preference card for an arthroscopy surgery used to identify the case cart near the OR (example 26). Right: diagrams on shelves to indicate placement of items for each surgery specialty (example 29).

Use visual management for the identification of spaces, resources, and processes										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
	26. Preference cards for OR set up could include BE recommendations - e.g., operating table, trolleys, equipment, and waste bin positions. To arrange the case carts, nurses can use the									

	preference cards as a checklist that can be attached to the cart to signalise the scheduled surgery and the corresponding OR. (O, I)									
	27. The ORs schedule should be displayed in a centrally located dashboard, helping staff to check room allocation. In nursing stations, there can be a board at the desk to quickly identify the patient's name and location according to the disposition of the bays and the list of day surgeries. (O, I)									
	28. To facilitate hospital wayfinding, the number of decisions required by users should be minimised, with progressive information disclosure, at the right time and order. Demarcating boundaries of different units and including singular elements are also strategies to reinforce people's mental maps. In restricted areas such as sterile corridors, visual signage must be provided – e.g., red lines in the floor. (I, R)									
	29. Shelves can have diagrams or pictures to inform staff. Storage can be managed by kanban systems – i.e., cards for visual and quick identification of replenishment order points. When store persons fill the shelves, barcodes can be scanned, and when a minimal inventory level is reached, it automatically orders a purchase. (O, I)									
	30. Outside signage should be incorporated indicating when lasers and x-rays are used in the OR – e.g., blinking lights - so staff should wear PPE to access or wait for the lights to turn off. (O, R)									
	Total of practical examples per areas/flows									
	2	**3**	**1**	**5**	**2**	**5**	**1**	**3**	**2**	**1**

Table 23 - Practical examples associated with the design prescription "use visual management for the identification of spaces, resources, and processes".

The prescription "provide slack resources to cope with disruptions" is associated with twelve examples (31 – 42), in Table 24. The most applicable example (31) relates to the role of people to complement signage in wayfinding. Also, BE preparedness for emergencies or pandemics is encompassed by several examples. For instance, BE adaptability to different types of uses (e.g., support areas that can be used for perioperative services) should be anticipated in design (37, 38, 40). Moreover, integrating emerging technologies requires spare points to connect devices expected to be released in the near future (39). The least applicable example (42) suggests allocating PACU patients between empty beds. It facilitates monitoring of patient conditions by the nursing station.

Provide slack resources to cope with disruptions										
Areas					**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical	**31.** In wayfinding, staff can complement signage with verbal instructions or guide patients to their destinations. (O, I, R)									
	32. Positive distractions mitigate stress for users, providing a welcoming environment – e.g., greenery and external views, decoration, artwork, colours, music, balconies to get fresh air in the staff room.									

Windows with blinds can be designed in the corridors for staff well-being. In ORs, windows must have blinds to control light and glare. (O, I, R).									
33. Place acoustic barriers when noisy equipment is close to patient bays, as this can increase anxiety and discomfort. (I, R)									
34. Anticipate the need for expansion – e.g., extra inventory spaces. (I, O, R).									
35. In case of fire, sufficient time for evacuation should be provided by delaying the fire and smoke propagation – e.g., resistance ceiling and floor, and dividing treatment areas with smoke-proof walls. Evacuation routes should have manual emergency call points. Slack areas should be designed on the safe side of the fire wall to accommodate people. The air handling system must be designed for the extra heat load of IT and medical imaging equipment. (R)									
36. In energy shortages, back-up power systems must be activated, and each OR must be provided with an uninterruptible power supply for critical equipment. (R)									
37. Plan multiuse spaces, including support areas that allow conversion to perioperative service – e.g., patient bays adjacent to the intraoperative area can be converted into ORs or be temporarily used as storage. (O, I, R)									
38. If there is no ICU bed available, patients can be transferred to PACU in a bay that should incorporate some ICU resources by adapting the BE. Alternatively, a "high-dependency unit" can be designed to provide intermediate care between PACU and ICU. (O, I)									
39. Provide spare connection points to incorporate emerging technologies that may need larger spaces. The anaesthetic machine is a long-lasting investment and might need to incorporate tablets for access to digital records that is a new process. (I, R)									
40. Trade-off between dedicated ORs and flexible ORs. In smaller services, flexibility could outweigh the benefits of specialisation. If flexibility is needed, ORs layout needs to be free from structural interference and induction rooms can have sliding doors to provide larger ORs. Note that flexibility can also cause disruptions - e.g., microscopes in the ophthalmological ORs hinder the workflows of other specialties. Either way, OR setup can differ even for the same specialty, according to surgeons´ preferences – e.g., sometimes they want the machine in a specific location even if cables are in the way. (O, I, R)									
41. For all patients, preoperative bays should accommodate family members. (O, I, R)									
42. When allocating recovery bays, the PACU leader must be sure that patients have an empty bay between them so a nurse can oversee two patients side-by-side. (I)									
Total of practical examples per areas/flows									
5	**7**	**7**	**7**	**7**	**5**	**8**	**1**	**1**	**1**

Table 24 - Practical examples associated with the design prescription "provide slack resources to cope with disruptions".

Table 25 presents ten practical examples (43 – 52) associated with the prescription "design for the prevention of infections and contamination". Corresponding examples refer to air-handling systems (43, 48), furniture, fixtures, and equipment (44), layout that allows grouping of patient cohort and separation of flows (45, 46, 49), materials and finishes that make it easier cleaning and maintaining (47), storage and manipulation of sterile instruments and materials (48), protocols for maintaining a sterile environment in the OR, and waste management (50, 51,52). The most applicable example (43) highlights the importance of air-handling systems in the OR, which should be the most sterile environment in the surgical service. The least applicable example (52) underscores the specificities of waste and flows and disposal of used instruments in the support areas.

Design for the prevention of infections and contamination										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**43.** All ORs should maintain temperature, humidity, and ventilation acceptable for infection prevention – e.g., positive air pressure with ultra-clean HEPA-filtered air handling systems. Each OR must have separate exhaust systems to reduce the risk of airborne spread. (R)									
	44. Dispensers and PPE should be distributed consistently with ease of access across the service. Curtains in patient bays should not touch the floor to avoid contamination. Waste bins should be non-touch, and mirrors may only be installed where hair touching does not compromise infection control and can help check cap and mask donning – i.e., near PPE and scrub bays. (O, R)									
	45. ORs should have enough space for manoeuvring without contaminating the instruments in the sterile field, whose boundaries can be demarcated by led lighting in the ceiling and colours in the floors (O, I).									
	46. Robotic surgeries should be allocated in larger ORs, as they require a specific surgeon workstation and more instruments and people, which can compromise sterility due to proximity. (O, I, R)									
	47. Joints between finishes and gaps should be sealed – e.g., OR walls should be finished with vinyl at full height. Design slip-resistant vinyl finishes with sealed joints and skirtings throughout the surgical service, especially when fluids are used, or blood splits can occur. (I, R)									
	48. Sterile storage areas should have air quality equivalent to the ORs, with HEPA filters and shelves at least 30 cm above the floor. A colour scheme can signalise the weight of sterile packs for manoeuvring to avoid holes or falls that compromise sterility during transport and storage. (O, I, R)									
	49. Changing rooms must be designed with two doors, according to staff flows: from semi-restricted areas to restricted areas. Similarly, contaminated areas should ideally have two accesses: an internal door through which the orderlies put the case waste and an external door for the back-of-house corridor where the housekeepers pick and take them to the hospital waste management room. (O, I, R)									
	50. Give visibility to sterile zones as much as possible such as by using disposable drapes to cover the operating table, trolleys, light handles, and robot arms. (O, I, R)									
	51. Corridors of the whole surgical service must have power plugs to enable cleaning. (O, I, R)									
	52. Disposal of used instruments should avoid occupational risks – e.g., sharp containers should contain indications. Clean utility rooms should be provided and dirty utility rooms for safe disposal of fluids. (O, I, R).									

	Total of practical examples per areas/flows									
	4	7	4	5	3	7	3	3	3	6

Table 25 - Practical examples associated with the design prescription "design for the prevention of infections and contamination".

The prescription "use technologies supportive of safe, efficient, and flexible workflows" (Table 26) encompasses eight examples (53 – 60). The most applicable example (53) highlights the importance of automatic doors in high-traffic areas. In these areas, anticipating patient needs during admission minimizes patient handling and corridor clutter (54). Further, installing multifunctional crash rails with handrails promotes safety in common areas and corridors (56). High-traffic areas can also have cloud-based digital wayfinding and assistive technologies to enhance navigation with updated information (59). In storage areas, dedicated lifts facilitate the transfer of sterile and contaminated items, enhancing infection control (55). Also, effective inventory management systems enhance resource allocation (57). In the OR, call systems can support the surgical team to obtain assistance from support areas (58).

Use technologies supportive of safe, efficient, and flexible workflows										
	Areas				Flows					
	Preoperative	Intraoperative	Postoperative	Support	Patient/ family	Staff	Equipment	Supplies	Sterile instruments and materials	Waste
Practical examples	**53.** Doors may open automatically in high-traffic areas - e.g., between OR and induction room. Such doors may have a manual override device in case of emergencies. (O, I, R)									
	54. The need for specific patient stretchers could be anticipated in the admission to reduce patient handling and stretchers in corridors. For instance, if a bariatric patient is admitted, a larger bed should be provided in the preoperative phase. Likewise, the need for high mattresses, ceiling-mounted lifting equipment, and large slings can be identified early. (I, R)									
	55. Sterile unit should have two dedicated lifts connected with the surgical service: a clean lift for sending out sterile items and a dirty lift to receive the used items. A mistake-proof device can be included in these lifts to prevent the trolley from moving and damaging sterile packs – e.g., a bar to be pushed against the trolley. (O, I, R)									
	56. Wall and corner protection is needed in the surgical service common areas and corridors due to the high flow of trolleys and equipment. (R)									
	57. In the storage rooms, mistake-proof devices can avoid placing small items behind big ones. (I, R)									
	58. Provide call systems with buttons inside ORs to signalise the supporting areas that orderlies and clinical staff are needed. Similar devices could be implemented to communicate to the surgical team that the patient waiting in the induction room is ready to enter the OR. (O, I, R)									

	59. Use cloud-based digital signage to allow for the customisation of information, such as preferred language and current use of spaces. Also, digital wayfinding can display the distance to a destination, contributing to reducing visitors´ anxiety. (R)									
	60. Workstation-on-wheels support ancillary tasks to be completed in surgical downtime, such as checking emails and paperwork. (O, I, R)									
	Total of practical examples per areas/flows									
	2	**4**	**2**	**6**	**5**	**3**	**5**	**2**	**1**	**1**

Table 26 – Practical examples associated with the design prescription "use technologies supportive of safe, efficient, and flexible workflows".

5.5 DISCUSSION

This surgical service case study provides evidence of the wider applicability of the design prescriptions, which had been previously analysed empirically only in the common areas in hospitals by Ransolin et al. (2024). This applicability suggests that the prescriptions are concerned with major themes in the BE design supportive of resilient health services. In fact, the prescriptions are applicable to activities and areas beyond the ORs, in which the main value-adding activity of the surgical service takes place. Both in healthcare and in other industries, support flows and corresponding areas are often those in which a large number of improvement opportunities might be identified (Copeland and Chambers, 2017; Moons et al., 2019). Thus, this study clarifies the need for a systems perspective when analysing the BE of surgical services that are not limited to the ORs, the unit of analysis of several prior studies (e.g., Neyens et al., 2019; Taaffe et al., 2023). At the studied service, ORs accounted for only 21% of the total floor area. By contrast, the support areas where most logistics processes took place consisted of 61% of the floor area. Moreover, 28 examples focused on the ORs (intraoperative areas), while 46 examples were related to the support, pre and postoperative areas. These findings can stem from both the much larger areas outside the ORs and the possible wider variety of activities that occur in these areas, which give rise to more variabilities that trigger RP. These results reinforce the need for RP in the internal logistics of hospitals (Göras et al., 2019), revealing that logistics within hospital units might be as relevant as logistics between units.

The systems orientation of the developed design knowledge is evident in the nature of the practical examples related to the prescriptions. For instance, examples 1 and 4 are mostly socially-oriented, avoiding mixing patients from distinct perioperative phases and with equipment, and sterile and dirty flows. These issues are influenced by technically-oriented examples (e.g., 5 and 6), which advocate for adequate dimensions of corridors and doorways and plain floor finishes. The prescriptions themselves are also inter-related. For instance, the prescription related to centralisation and decentralisation of resources impacts the walking distances within the surgical services, influencing the prescription of design routes between perioperative phases. Also, some of the examples of technologies supportive of workflows (e.g., two lifts at the sterile unit) play a role as slack resources.

In addition, the design knowledge might enhance the four potentials of resilient systems, namely monitoring, anticipating, responding, and learning (Hollnagel, 2017). This connection can be exemplified based on the recurrent theme of crossings between the flows of dirty items and patients. For instance, when **responding** to a situation where a lift is out of service, patient flows need to be prioritised over the dirty flows - indicated in example 25, on the use of signage for patient-dedicated use. In addition, staff members can provide information and thus act as slack resources to wayfinding, as indicated in the prescription of slack resources (example 31). In this scenario, **monitoring** can relate to example 20, concerned with managing dirty item flows, especially in single corridor layouts. These flows can be monitored with the support of wayfinding strategies – e.g., 28 and 59, respectively, addressing the use of digital wayfinding to track flows in real-time. **Anticipating** crossing flows is related to example 1, concerned with conducting mock-ups to verify these flows in practice. **Learning** might result from the continuous updating and refinement of the design knowledge, as well as from the feedback from users of the BE.

The proposed design knowledge can also be analysed in light of the micro, meso, and macro levels of health services, which is a commonly adopted analytical framework in the resilient healthcare literature (Berg et al., 2018). In fact, the design of resilient systems tends to benefit from explicitly interrelated designs at all levels (Disconzi and Saurin, 2024). The results of this study can be positioned primarily as a contribution to the design of resilient systems at the micro level. Indeed, despite the significant area, the surgical service is only one of several hospital units and occupies only 10% of the total hospital area. There are secondary implications at the meso level, related to the interactions between the surgical service and other units. These were visible, for instance, in all examples related to instruments that move from the sterile unit to the surgical service and then back. At the macro level, regulations could make it explicit that certain requirements are particularly important to support RP. Regulations might be assets for resilient healthcare as they promote designs and structures for RP across health systems (Øyri and Wiig, 2022; Macrae, 2019).

Figure 18 summarizes the main relationships between the elements of the proposed design knowledge. It depicts the connections between the BE knowledge levels (i.e., prescriptions and examples), application focus (i.e., BE areas and workflows), and RP as the end goal of using such knowledge. Figure 18 also highlights the emergent nature of RP (Wachs et al., 2016), arising from the interactions between the BE and workflows. The logical connections between the prescriptions and RP, referred to in Figure 18, were presented in Table 16.

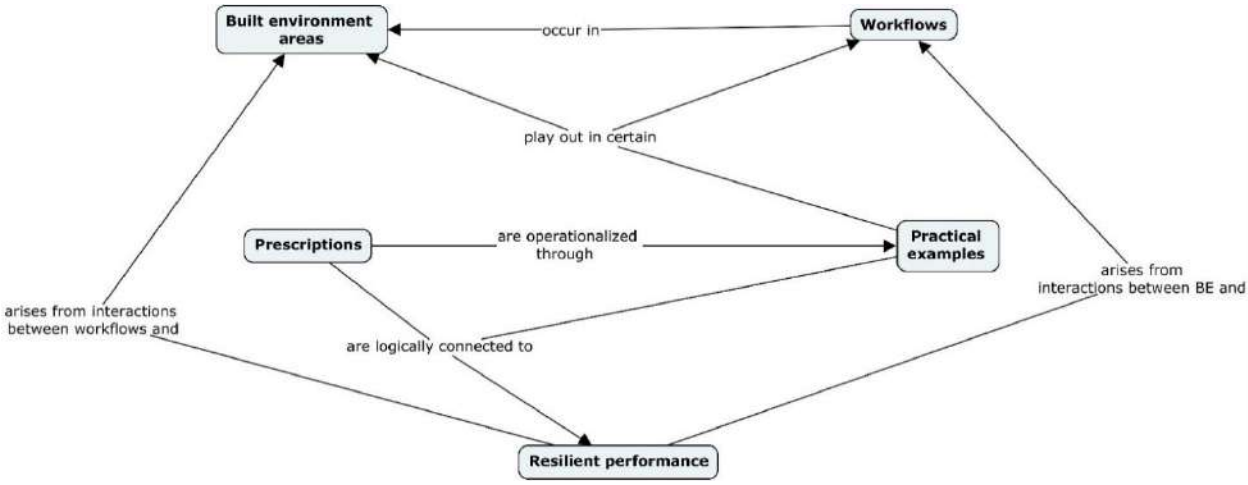

Figure 18 – Relationships between the elements of the proposed design knowledge.

The prescriptions were relevant to all studied service flows, thus probably being of interest to surgical services other than the one studied. The practical examples are also of general interest, although their scope of application is relatively more context-dependent. Although such contextual influences make any generic prioritisation elusive to some extent, we suggest that all prescriptions and examples with direct implications to the safety and well-being of patients and providers take priority over the others. Stakes are high in these settings, and patient-centred models of care provision have been widely recognized as crucial (Acher *et al*., 2015; Rosa *et al*., 2018).

Finally, it is worth noting that the neglect of the design knowledge can hinder not only RP but also other performance dimensions of surgical services such as safety and efficiency. Neyens et al. (2019) and Wahr et al. (2013) reported that layout and equipment positioning significantly influenced disruptions in the operating room, creating risks of surgical site infections. In this regard, example 21 (prescription 'give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility') highlights strategies to avoid clutter and risks of slips, trips, and falls – e.g., power plugs evenly distributed to reduce the use of cords and cableless equipment. Moreover, example 39 (prescription 'provide slack resources to cope with disruptions') refers to equipment´s connection points to incorporate emerging technologies, which if not well integrated with existing systems can contribute to errors due to the need to constantly switching tasks and equipment (Jurewicz et al., 2021). As a more general consideration, Rapport et al. (2020) reported the negative impacts of unfit-for-purpose workspaces on the work and well-being of surgical staff and patients.

5.6 CONCLUSIONS

The research question that guided this study was concerned with how to develop BE design knowledge supportive of RP in the internal logistics and perioperative areas of surgical services. A case study of a surgical service indicated that the prescriptions adopted as a point of departure were totally applicable to this setting, demanding only minor tailoring of the original statements for context. The prescriptions also served as a data analysis framework, allowing for the identification of 60 practical examples that addressed a variety of interactions between the areas and workflows of the surgical service, highlighted in Tables 5 to 11. Thus, the design knowledge might be framed as a set of prescriptions, examples, and their association with workflows and areas. Only the prescriptions stemmed from a prior study, therefore indicating the originality of this investigation.

The novelty of this study also lies on its systems perspective that considered areas and flows that play out outside of the operating rooms, the main unit of analysis of prior studies. Thus, this study is consonant with the resilience engineering proposition that RP is an emergent property of the interactions between a wide range of technical and social elements. Connections with resilience engineering were also made explicit in the rationale for the prescriptions and when linking the findings to the four resilience potentials and the micro, meso, and macro levels of healthcare systems. For practitioners, the design knowledge is valuable not only for BE designers but also for regulators and hospital managers during the design (or redesign) of surgical services.

Limitations of this study should also be acknowledged. First, findings resulted from the case study of a private medium-sized hospital, which is a setting with relatively fewer complex flows than larger and public hospitals where greater variety of patients and processes are likely to be found. Second, the prescriptions were not implemented during a new BE design or intervention of a surgical service. Third, depending on organisational factors (e.g., budgetary limitations), it might not be possible for all prescriptions to be implemented. Fourth, indoor environmental quality factors were not explored in depth, even though they were addressed by some practical examples – e.g., example 32 mentions the need for blinds in the operating room windows to control light and glare; 33 advises acoustic barriers in patient bays, and 43 recommends that all operating rooms should maintain temperature, humidity, and ventilation acceptable for infection prevention.

This study gave rise to opportunities for future studies, as follows: (i) implement the design knowledge in the redesign of the studied surgical service and others; (ii) adapt or develop new design prescriptions for other health services; (iii) investigate how the design knowledge can contribute to improve regulations and good practices in BE surgical service design and operations; (iv) investigate the interactions between the surgical service flows and broader health services, along with BE implications – e.g., staff flows to and from the hospital warehouse and sterile unit; (v) contrast different sites and settings in a larger, longitudinal study with an international focus.

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6 DISCUSSION AND CONCLUSIONS

The research objective of this doctoral thesis was **to propose a framework of built environment design knowledge supportive of resilient internal logistics in hospitals**. This chapter articulates the results from the previous chapters and presents the framework that addresses the research objective.

6.1 CONTRIBUTIONS OF THE THESIS

The framework stems from the results of the three papers that form the core of this thesis, presented in chapters 3, 4, and 5. The knowledge structure is the main finding from the systematic literature review, which is also applied in the thesis case studies for data analysis and results presentation. The framework´s elements encompass four meta-principles, seven principles, seven prescriptions, 181 practical examples of applying the prescriptions, in addition to the indication of BE areas and workflows where the knowledge should be applied. The end goal of applying this knowledge is to design a BE supportive of resilient internal logistics in hospitals.

Figure 19 presents a schematic representation of the framework elements. At the two highest abstraction levels, the framework is composed of four meta-principles based on complexity theory, and seven principles that provide design guidance to BE supportive of RP in health services in general, not being specific to hospital internal logistics. These elements were generated in the systematic literature review and were preserved in the subsequent case studies. The lower-level elements of the framework were also present in the following studies, containing variations to embrace the particularities of the different hospital settings while linking the knowledge structure with varied hospital internal logistics flows. At the next level, the framework is composed of seven design prescriptions, which can be interpreted as applications of the principles to the context of hospital internal logistics. The lowest level of abstraction is composed of 181 practical examples, of which 108 are related to hospital internal logistics, reflecting the insights from the two case studies that addressed logistics to and from ICUs, and within surgical services. As indicated in the case studies, the levels of meta-principles, principles, and prescriptions can serve as a heuristic device to support thematic analysis for the generation of context-specific knowledge. What is more, the level of prescriptions is key to the development of context-specific knowledge in the realm of internal hospital logistics. Indeed, essentially the same set of prescriptions allowed to produce design knowledge for two different contexts of internal logistics. Therefore, the prescriptions depicted in Figure 19 play a key role to answer the main research question of the thesis. As such, the proposition is made that the same research method used in papers 2 and 3 can be replicated to produce design knowledge for resilient internal logistics in other areas of hospitals.

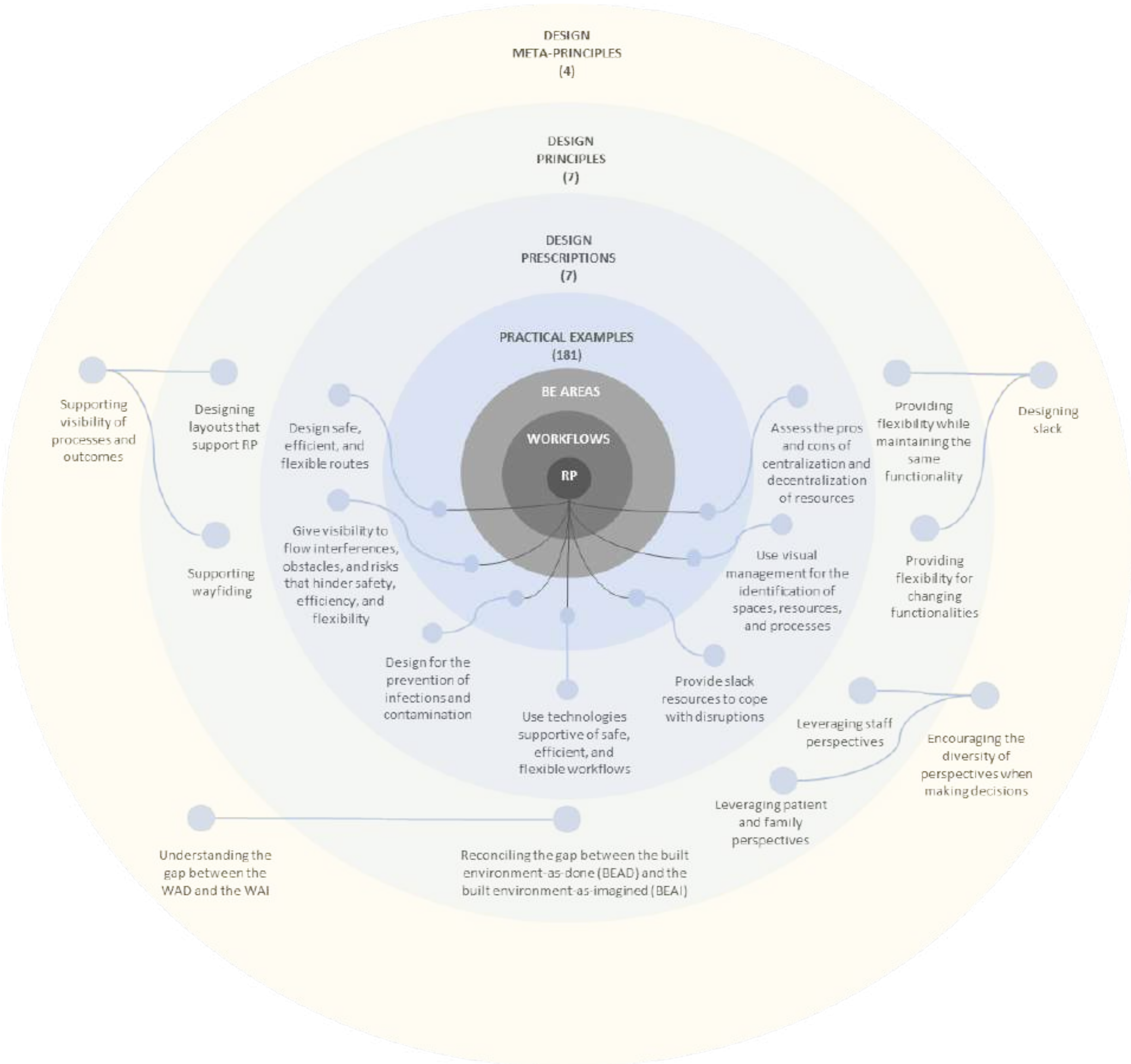

Figure 19 - Framework of **b**uilt environment design knowledge supportive of resilient performance in the internal logistics of hospitals.

The sequencing of the thesis´ papers reflects this journey from higher to lower abstraction levels. Thus, meta-principles were relevant for thematic analysis in the first paper, for grouping practical examples from EBD literature and supporting the subsequent generation of design prescriptions and principles. Then, in the second paper, those design principles were the starting point for data analysis of the case study of BE supportive of resilient logistics to and from ICUs, giving rise to context-specific prescriptions. Next, in the third paper, those prescriptions serve as a data analysis template for the development of BE design knowledge supportive of resilient logistics in surgical services. The implications of the design knowledge to the four potentials for resilient systems – i.e., responding, monitoring, learning, and anticipating – were also discussed (Hollnagel, 2017). The interdependent and complementary nature of the resilient potentials present in complex health services is also reflected in the interconnection of the elements of the framework. It is recommended the combined application of design prescriptions to activate each potential (and vice-versa) as one design prescription can be related to more than one resilient potential. Therefore, the resilient potentials were useful to discuss which abilities the knowledge framework contributes to when promoting a BE supportive of RP.

The relationships between the elements of the design knowledge framework are schematically displayed in Figure 18 presented in the third paper. In both Figures 19 and 20, the interactions between the BE and workflows take a central stage, highlighting the point that their interactions give rise to RP. The links between BE areas, workflows, and RP were made explicit in the presentation of the practical examples of applying the prescriptions in both case studies. In this regard, it is worth emphasizing that the proposed design knowledge aims at supporting resilient internal logistics in everyday work of hospitals, which was the context observed in both case studies. In this respect, data were collected mostly from observations and interviews with staff members, reflecting work-as-done. In addition, the second paper included a resilience-based approach to support the analysis of the implications of neglecting the BE design knowledge for RP.

The set of workflows investigated in the case studies is another thesis contribution. While the literature points out seven generic hospital flows – i.e., patients, family, providers, medication, supplies, information, and equipment (Black and Miller, 2008), the case studies deepened the categories of flows to specific hospital settings depending on their contextual importance. The study on the logistics activities to and from ICUs devised the BE design knowledge according to 11 flows – i.e., people (resuscitation, exams, admission, discharge, visitors) and supplies (drugs and medical materials, dietary, sterilized materials, cleaning, clothing, waste). In turn, the study on surgical services depicts the knowledge into six main flows – i.e., patient/family, staff, supplies, equipment, sterile instruments and materials, and waste - contrasting with the literature on surgical services that differentiate staff flows into surgical and anaesthesiology team and disregards the flows of nurses, orderlies and other support teams (Machry et al., 2021).

Furthermore, the framework is fractal in the sense of being potentially relevant to the micro, meso, and macro levels of health services. At the micro level, the design knowledge was developed for the internal logistics of a single hospital unit, namely surgical services, although also considering the implications for the meso level when discussing the interactions of the surgical service with other hospital units – e.g., in the logistics processes involved in the flows of sterile instruments. At the meso level, design knowledge was devised for the logistics activities to and from ICUs. At the macro level, the framework can be used for the identification of regulatory requirements most supportive of RP in the internal hospital logistics. The fractality and the interconnection of elements at different levels of abstraction in the knowledge framework provide guidance that can be more beneficial depending on the scope of different design or intervention stages of the BE and health services. Ideally, the knowledge should be considered as early as possible in the design stages of BE and health services, as the chances of achieving impactful outcomes are higher. The expertise of professionals involved in the initiatives to support RP is also an important factor during the framework application. Thus, the BE can be designed to fit the purposes of the system for expected conditions based on past experiences while supporting RP by anticipating performance adaptations for unexpected conditions. Regarding the application of the framework during the design or intervention stages of the BE and health services, simulations and workshops are helpful approaches to testing and refining the proposed solutions based on scenarios – e.g., through the use of personas to illustrate patient journeys. These sessions should account for a range as wide as possible of stakeholders to allow different perspectives - i.e., patients, visitors, managers, staff members, and directory board – and can also be helpful to train professionals on how to consider the knowledge. Considering the long timeframe from BE design to use and the possibility of sharing learning across organisations, an electronic repository can facilitate the update and uptake of the framework in the health service life-cycle in accessible language and interfaces for academics and practitioners. The framework can also be used later in health service usage to find improvement opportunities or mitigate major disruptions in the system - e.g., knowledge to inform committees that are formed to face the consequences of pandemics.

Further, it is important to acknowledge that not all prescriptions are equally affordable by different hospitals, and trade-offs between design solutions might be necessary to support decision-making. For example, when the lack of financial resources imposes constraints on health services, the framework can contribute to assigning priorities based on investigating the WAD in the service flows. This is due to the fact that, although complementary, the design prescriptions can be conflicting – e.g., designing for the prevention of infections can imply isolated spaces that hinder the visibility of service flows. The design prescriptions and examples are context-dependent, making generic prioritisation elusive to some extent. Above all, prescriptions and examples with direct implications to the safety and well-being of patients and staff members should be prioritised.

Rather than a template for full compliance, the knowledge must be regarded as a source of insights, helping to identify practical examples of the BE implications to RP that otherwise could have remained concealed in the system´s performance. The BE influence on workflows and RP has also been discussed by other theories and studies not explicitly related to EBD, such as patient-and-family-centered care (Choi & Bosch, 2013; France et al., 2009), healthcare complexity (Rapport et al., 2020; Ransolin et al., 2020), safety science (Pati et al., 2016; Sundberg et al., 2020a), human factors and ergonomics (Platt et al., 2017; Battisto e al., 2009), and lean healthcare (Karvonen et al., 2017; Copeland & Chambers, 2017). Safety and efficiency are also addressed in studies reporting, for example, the impact of layout and equipment positioning on work disruptions and risks of surgical site infections in the OR (Neyens et al., 2019; Wahr et al., 2013).

A further contribution of this thesis relies on the focus on resilient hospital internal logistics, which is currently an under-explored topic in the EBD and resilient healthcare literature. As such, qualitative methods were used to investigate the nuances of the WAD of diverse hospital workflows and their interactions, demanding a great effort for data collection and analysis. The case studies followed two steps – i.e., characterisation of the health service flows and BE and the development of the design knowledge - which can be replicated in several health service contexts. Resilient healthcare research can benefit from the method used in this thesis to explore the interaction between the system´s elements that go beyond the BE, e.g., organisational aspects and technologies with care models, and its influence on RP.

Consequently, the framework can be of interest to an international readership of academics and practitioners, as different contexts and healthcare levels are discussed in light of complexity, and resilient engineering literature. The framework is an original contribution expected to guide both BE and operations designers in health services.

6.2 LIMITATIONS

Some limitations of this thesis must be highlighted. Firstly, the framework was conceived based on a resilience engineering perspective, which privileges everyday work. Thus, RP to cope with natural or man-made disasters was not the focus of this research study. Also, other approaches might be complementary to this work, such as operations management and risk assessment. Secondly, the case studies were conducted in teaching hospitals, meaning participants tend to recognize the value of research, which may not be the reality for other hospital types. This leads to the third limitation, regarding the contextual differences between health settings – e.g., size, budget, and values - which can impact the applicability of the findings. Fourth, the framework derived in this thesis was not applied during the BE design or intervention of health services. Fifth, the influence of BE on RP was not quantified in terms of the impacts on health outcomes and efficiency.

6.3 SUGGESTIONS FOR FUTURE RESEARCH

Finally, further research can investigate the following aspects: (i) the application of the framework during the BE design or intervention of health services, with simulations and workshops to test and refine design solutions along with a wide range of stakeholders and training to educate professionals on how to consider the knowledge; (ii) the incorporation of the design prescriptions and examples during the process of requirements management and BIM-based software; (iii) the use of the framework for developing methods to assess BE design, renovations, and post-occupancy evaluation to verify their support to RP; (iv) developing an electronic repository to facilitate the uptake of design knowledge, in accessible language and interfaces for academics and practitioners, for the continuous updating of EBD in the health service life-cycle from design to usage; (v) investigate the possibility of incorporating design prescriptions into regulations and standards; and (vi) replicating the application of the framework in other hospital processes for developing further design knowledge.

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APPENDIX A – Ethics Approvals (Case Study I)

UFRGS - HOSPITAL DE CLÍNICAS DE PORTO ALEGRE DA UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL ¿ HCPA

PARECER CONSUBSTANCIADO DO CEP

DADOS DA EMENDA

Título da Pesquisa: Desenvolvimento de Novos Métodos para Gestão de Operações em Sistemas de Saúde: estudos em um hospital

Pesquisador: Ricardo de Souza Kuchenbecker

Área Temática:

Versão: 10

CAAE: 79424617.0.0000.5327

Instituição Proponente: Hospital de Clínicas de Porto Alegre

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 4.041.484

Apresentação do Projeto:

Serviços de saúde são exemplos de sistemas sócio-técnicos complexos (SSC), visto que possuem características como variabilidade, incerteza, diversidade de elementos (sejam eles técnicos, sociais e organizacionais) que interagem dinamicamente. Tais características, em conjunto com as pressões por eficiência e a evolução tecnológica, com potencial para acidentes de grande impacto, têm despertado crescente interesse profissional e acadêmico pelo uso de novas abordagens de gestão de operações em sistemas de saúde. Nesse contexto, os métodos de modelagem, gestão e simulação de operações em ambientes hospitalares devem ser compatíveis com a natureza complexa desses ambientes. Novas lentes teóricas, como a engenharia de resiliência (ER) constituem uma opção para o desenvolvimento de práticas gerenciais mais eficientes, eficazes e seguras. A presente proposta de pesquisa trata do desenvolvimento de novos métodos de gestão de operações em ambientes hospitalares, abordando os mesmos como SSC, sob a perspectiva da ER e tem como objetivos específicos: (a) desenvolver um método para avaliar e influenciar, por meio de decisões e ações gerenciais, as interações entre fluxos hospitalares; (b) desenvolver um método para modelar e influenciar redes sociais de resiliência em ambientes hospitalares; (c) desenvolver um método para avaliar o uso do princípio da produção puxada em ambientes hospitalares;(d) desenvolver um método para gestão de requisitos operacionais e do ambiente

Endereço: Rua Ramiro Barcelos 2.350 sala 2229
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UF: RS **Município:** PORTO ALEGRE
Telefone: (51)3359-7640 **Fax:** (51)3359-7640 **E-mail:** cep@hcpa.edu.br

construído em hospitais e desenvolver diretrizes de resiliência para lidar com as variabilidades diárias nos sistemas de saúde, associadas ao projeto do ambiente construído; (e) desenvolver um método para avaliar a geração de valor, considerando a interação entre fluxos de pessoas e ambiente construído para o serviço de saúde; (f) compreender a influência da mudança de layout na atuação do TRR, identificando estratégias para mitigar esse impacto; (g) desenvolver um método para avaliar a transparência de processos no hospital, com foco no fluxo do paciente, bem como a extensão pela qual essa é influenciada pelo nível de complexidade estrutural e funcional da área estudada; (h) caracterizar a gestão em diferentes ambientes complexos considerando as diretrizes de SSC.

Objetivo da Pesquisa:

Objetivo geral

O objetivo geral deste projeto é o desenvolvimento de métodos inovadores para gestão de operações em hospitais, adotando as perspectivas da complexidade e da engenharia de resiliência.

Objetivos específicos

(a) Desenvolver um método para avaliar e influenciar, por meio de decisões e ações gerenciais, as interações entre fluxos hospitalares, relativos à assistência a pacientes atendidos na instituição;
(b) Desenvolver um método descrição e melhoria das redes sociais de resiliência em ambientes hospitalares;
(c) Desenvolver um método para avaliar o uso do princípio da "produção puxada" em processos de produção assistenciais em ambientes hospitalares;
(d) Desenvolver um método para gestão de requisitos operacionais e do ambiente construído em ambientes hospitalares – Esse objetivo foi endereçado pela dissertação de mestrado da pesquisadora. O objetivo atual do subprojeto D, a ser endereçado na tese de doutorado da aluna é: desenvolver diretrizes de resiliência para lidar com as variabilidades diárias nos sistemas de saúde, associadas ao projeto do ambiente construído;
(e) Desenvolver um método para avaliar a geração de valor a partir da interação entre fluxos de

pessoas e ambiente construído para o serviço.
(f) compreender a influência da mudança de layout na atuação do TRR, identificando estratégias para mitigar esse impacto.
(g) Avaliar a influência da complexidade estrutural e funcional do ambiente hospitalar na transparência de processos, com foco no fluxo do paciente.
(h) Caracterizar a gestão em diferentes ambientes complexos considerando as diretrizes de SSTC.

Avaliação dos Riscos e Benefícios:
Riscos

Não são conhecidos riscos decorrentes da participação dos sujeitos nessa pesquisa, porém poderá haver algum desconforto pelo tempo necessário para a realização da entrevista e/ou questionário, grupos focados. Estima-se que o tempo máximo não ultrapasse 1 hora.

Benefícios esperados para o HCPA

Como decorrência deste projeto, os seguintes benefícios são esperados para o HCPA:

(a) Identificação de oportunidades de melhorias operacionais e de condições de trabalho nas áreas objeto dos estudos. Este benefício corrobora o argumento exporto por Sikka et al (2015) sobre a necessidade de contemplar a melhoria da experiência dos profissionais no processo cuidar.

(b) Apoio para implementação das oportunidades identificadas, conforme a disponibilidade de recursos e prioridades do HCPA;

(c) Capacitação dos profissionais do HCPA diretamente envolvidos no projeto (por exemplo, supervisores e lideranças de áreas), visto que a coleta, análise e disseminação interna de resultados será feita de modo participativo, sempre que possível consultando os profissionais;

(d) Publicações em conjunto com os profissionais do HCPA diretamente envolvidos no projeto, em congressos e periódicos.

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Bairro: Santa Cecília **CEP:** 90.035-903
UF: RS **Município:** PORTO ALEGRE
Telefone: (51)3359-7640 **Fax:** (51)3359-7640 **E-mail:** cep@hcpa.edu.br

Ao final de cada sub-projeto, um relatório com os resultados do mesmo será entregue ao HCPA, detalhando sugestões de como operacionalizar os benefícios mencionados acima. Além disso, as reuniões para retorno dos resultados constituirão oportunidades para discussão presencial dos resultados com a equipe do HCPA.

Comentários e Considerações sobre a Pesquisa:
Emenda 07 na PB submetida em 11/05/2020.
Justificativa:
O adendo proposto complementa um objetivo específico ao projeto. As inclusões estão sinalizadas em vermelho, no arquivo intitulado "Projeto_Clínicas_2017_com_alteracoes_sinalizadas". As inclusões contemplam: alteração no objetivo específico, alteração na descrição do sub-projeto, inclusão de etapas, procedimento de coleta e análise dos dados na seção de método, e cronograma.
Além disso, solicitou-se via vistema AGHUSE a prorrogação do prazo para 31 de maio de 2021 (anexo F) do projeto.

Principal alteração no projeto:
" 3.2.4 Etapas do Sub-Projeto D: Gestão de Requisitos

(a) Revisão bibliográfica: essa etapa permeará toda a pesquisa, tratando dos tópicos ambiente construído em instalações de assistência à saúde, engenharia de resiliência, gestão de requisitos e BIM.

(b) Seleção do sistema-alvo: conforme já mencionado, a(s) unidade(s) a ser(em) estudada(s) será(ão) definida(s) em conjunto com representantes do HCPA. A princípio a(s) unidades selecionada(s) é a mesma para os oito sub-projetos. Esta etapa inclui, após seleção dos sistemas-alvo, encontro com representantes do(s) mesmo(s) para apresentar projeto de pesquisa.

(c) Compreensão do contexto, dos processos e principais fluxos dos usuários: essa etapa será composta por análise de documentos, observações não participantes e entrevistas semiestruturadas (Apêndice I). O número de entrevistados será definido pelo critério da saturação teórica, ou seja, as entrevistas serão finalizadas quando não surgirem novas informações e padrões emergirem dos resultados. Esta etapa é fundamental para o desenvolvimento das etapas subsequentes. Cabe ressaltar que neste sub-projeto, entende-se por usuário os funcionários, pacientes e familiares ou acompanhantes.

(d) Identificação de requisitos: essa etapa busca identificar os principais grupos de requisitos: (1) requisitos legais e regulamentares, pertinentes ao ambiente construído; (2) requisitos dos principais usuários, pertinentes ao ambiente construído; e (3) requisitos do ambiente construído, que não sejam ligados a um grupo específico de usuários, mas tenham impacto em todos os grupos. Os requisitos legais e regulamentares se relacionam a requisitos do edifício e do serviço de saúde e segurança que influenciam a sua operação (KAMARA et al., 2000). Os requisitos dos usuários constituem uma declaracao das necessidades a serem atendidas pela edificacao, incluindo aspectos tecnicos, fisiologicos, psicologicos e sociologicos (CIB, 1982). Esses requisitos definem condicoes e facilidades a serem fornecidas pela edificacao para propositos especificos (CIB, 1982). Já os requisitos do ambiente construído descrevem o ambiente imediato em torno do local da instalação (KAMARA et al., 2000), tais como os espaços edificados, o mobiliário, os equipamentos, etc.

(e) Modelagem de interações: para a modelagem, serão definidos junto com a equipe do hospital os principais fluxos de atividades e os espaços a serem analisados. Será necessário o acesso ao projeto arquitetônico no formato digital (DWG), através de plantas-baixa e cortes contendo a distribuição do mobiliário e equipamentos. Essa modelagem auxiliará na compreensão dos fluxos selecionados e das suas interfaces com outros espaços. O modelo tridimensional será desenvolvido no software Autodesk Revit Architecture (versão educacional). Por sua vez, a modelagem BIM de requisitos trata-se de uma etapa que cruza informações dos requisitos dos usuários com os requisitos do ambiente construído. Após as observações e entrevistas será possível identificar as funções do processo analisado e os requisitos dos usuários em relação às operações, ao ambiente construído. Pretende-se validar as informações capturadas nas etapas anteriores e identificar novos requisitos com o auxílio da abordagem FRAM, junto aos grupos de usuários desses processos. Também serão usadas plataformas BIM para modelagem arquitetônica,

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Telefone: (51)3359-7640 **Fax:** (51)3359-7640 **E-mail:** cep@hcpa.edu.br

armazenamento dos requisitos coletados e conexão entre ambos. Assim, os requisitos serão estruturados e inseridos no software norueguês de gestão de requisitos, intitulado dRofus (adquirido pelo Programa de Pós -Graduação em Engenharia Civil da UFRGS com finalidade acadêmica), criado para uso em ambientes hospitalares. Na sequência, a estrutura de requisitos armazenados no dRofus será conectada ao modelo tridimensional, desenvolvido no Autodesk Revit Architecture.

(f) Análise da resiliência:
Para o cumprimento desses requisitos nos projetos de instalações hospitalares é necessário um profundo entendimento do trabalho real realizado pelos usuários, em vez de confiar no conjunto de regras que determinam como o trabalho deve ser executado. Neste subprojeto a lacuna WAD vs. WAI é reinterpretada em termos de Built Environment-as-Done (BEAD) e Built Environment-as-Imagined (BEAI). A desconformidade com os requisitos durante a fase de projeto da construção é uma fonte de variabilidade prejudicial nos serviços de saúde, exigindo dos usuários esforços extras de resiliência para atender a demanda, criando uma lacuna maior entre o BEAI e o BEAD. É escasso o conhecimento sobre a natureza desse desempenho resiliente, em que medida ele pode ser impedido em projetos de instalações hospitalares, em que medida é inevitável, como evolui com o tempo e quais são suas consequências não intencionais. Portanto, busca-se investigar os esforços resilientes desempenhados pelos usuários para lidar com a desconformidade dos requisitos do ambiente construído previstos em projeto. Nesta tese de doutorado, o Método de Análise de Ressonância Funcional (FRAM) é adotado como uma abordagem para compreender a diferença entre BEAD e BEAI, o desempenho resiliente correspondente, bem como os impactos na segurança e bem-estar do paciente.

(g) Desenvolvimento do artefato:
A partir da modelagem das interações, nessa etapa serão desenvolvidas as diretrizes de resiliência para lidar com as variabilidades diárias nos sistemas de saúde, associadas ao projeto do ambiente construído.

(h) Recomendações de melhoria: o modelo FRAM e a modelagem de requisitos poderão contribuir com melhorias para o espaço analisado e para as operações, na medida que possibilitarão a visualização de questões e interferências de ambos os aspectos relacionados ao ambiente construído que interferem nas operações, e vice-versa. Como consequência, serão disseminados os mecanismos de resiliência utilizados diariamente pelos usuários para lidar com impacto da desconformidade dos requisitos do ambiente construído nas operações. O artefato a ser desenvolvido, por sua vez, será dirigido aos profissionais responsáveis pelo processo de desenvolvimento de projetos do ambiente construído, para considerarem os requisitos e a resiliência diária dos usuários de forma visual e com maior facilidade.

As recomendações de melhoria serão desenvolvidas em conjunto com profissionais representantes do sistema-alvo. Ao longo de todo o período da pesquisa, resultados parciais serão discutidos com representantes das áreas afetadas no HCPA, preferencialmente em reuniões abertas e/ou grupos focados a todos os profissionais interessados."

Considerações sobre os Termos de apresentação obrigatória:

Foram incluídos os seguintes documentos:
- Carta de justificativa da emenda
- Projeto Detalhado com alterações sinalizadas (este arquivo apresenta em vermelho todas as alterações realizadas);
- Projeto Detalhado com alterações (este arquivo apresenta o projeto completo sem as marcações em vermelho);

Recomendações:

Lembramos que em razao da recente pandemia de COVID-19 as atividades de pesquisa possuem algumas restricoes. Em caso de duvidas, consultar o Grupo de Pesquisa e Pos-Graduacao (GPPG) para mais informacoes.

Conclusões ou Pendências e Lista de Inadequações:

A emenda não apresenta pendências e está em condições de aprovação.

Considerações Finais a critério do CEP:

Emenda 07 na PB submetida em 11/05/2020 aprovada, inclui Projeto de 11/05/2020.

Endereço: Rua Ramiro Barcelos 2.350 sala 2229
Bairro: Santa Cecília **CEP:** 90.035-903
UF: RS **Município:** PORTO ALEGRE
Telefone: (51)3359-7640 **Fax:** (51)3359-7640 **E-mail:** cep@hcpa.edu.br

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_1554698_E7.pdf	11/05/2020 15:11:58		Aceito
Outros	Carta_ao_Comite_11maio2020.docx	11/05/2020 15:08:23	Priscila Wachs	Aceito
Projeto Detalhado / Brochura Investigador	Projeto_Clinicas_2017_com_alteracoes_sinalizadas.docx	11/05/2020 15:07:49	Priscila Wachs	Aceito
Projeto Detalhado / Brochura Investigador	Projeto_Clinicas_2017.docx	11/05/2020 15:07:13	Priscila Wachs	Aceito
Outros	delegacao_de_funcoes_para_a_equipe_de_pesquisa_Boniatti.pdf	20/01/2020 16:10:25	Priscila Wachs	Aceito
Outros	termo_de_compromisso_para_utilizacao_de_dados_institucionais_Boniatti.pdf	20/01/2020 16:10:01	Priscila Wachs	Aceito
Outros	Carta_ao_Comite_emenda5.docx	20/01/2020 16:09:40	Priscila Wachs	Aceito
Outros	Carta_ao_Comite_nov2019.docx	04/11/2019 10:51:01	Priscila Wachs	Aceito
Outros	Carta_ao_Comite_emenda4_resposta_pendencia.docx	29/09/2019 09:25:48	Priscila Wachs	Aceito
Outros	Delegacao_Funcoes_Caroline_Zani.pdf	29/09/2019 09:24:46	Priscila Wachs	Aceito
Outros	TCUDI_Caroline_Zani.pdf	29/09/2019 09:23:48	Priscila Wachs	Aceito
Outros	Carta_ao_Comite_emenda4.docx	21/08/2019 22:21:06	Priscila Wachs	Aceito
Outros	Carta_ao_Comite_emenda3.docx	27/03/2019 15:27:15	Priscila Wachs	Aceito
Outros	Relatorio_de_Pesquisa_2019_02_21_13_13.pdf	15/03/2019 16:43:19	Priscila Wachs	Aceito
Outros	Carta_ao_Comite_emenda2.docx	06/08/2018 16:15:03	Priscila Wachs	Aceito
Outros	Carta_ao_Comite.docx	16/01/2018 13:54:18	Priscila Wachs	Aceito
Outros	termo_de_compromisso_para_utilizacao_de_dados_institucionais_assinado.jpeg	19/12/2017 14:34:26	Priscila Wachs	Aceito
Outros	delegacao_de_funcoes_para_a_equipe_de_pesquisa_assinado.jpeg	19/12/2017 14:33:56	Priscila Wachs	Aceito
Outros	Carta_Resposta_ao_parecer_2430177.docx	19/12/2017 14:33:00	Priscila Wachs	Aceito

TCLE / Termos de Assentimento / Justificativa de Ausência	TCLE_paciente_familiar_ou_cuidador.doc	19/12/2017 14:31:55	Priscila Wachs	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	TCLE_funcionarios.doc	19/12/2017 14:31:47	Priscila Wachs	Aceito
Folha de Rosto	Folha_de_Rosto_Assinada.pdf	18/10/2017 13:35:59	Priscila Wachs	Aceito

Situação do Parecer:
Aprovado

Necessita Apreciação da CONEP:
Não

PORTO ALEGRE, 21 de Maio de 2020

Assinado por:
Têmis Maria Félix
(Coordenador(a))

Endereço: Rua Ramiro Barcelos 2.350 sala 2229
Bairro: Santa Cecília **CEP:** 90.035-903
UF: RS **Município:** PORTO ALEGRE
Telefone: (51)3359-7640 **Fax:** (51)3359-7640 **E-mail:** cep@hcpa.edu.br

APPENDIX B – Ethics Approvals (Case Study II)

Medicine & Health Sciences Subcommittee
Macquarie University, North Ryde
NSW 2109, Australia

15/11/2022

Dear Dr Clay-Williams,

Reference No: 520221248843909
Project ID: 12488
Title: Built environment knowledge for resilient performance in surgical units_HREA

Approval date: 15 November 2022

Thank you for submitting the above application for ethical review. The Medicine & Health Sciences Subcommittee has considered your application.

I am pleased to advise that ethical approval has been granted for this project to be conducted by Dr Clay-Williams, and other personnel: Prof Frances Rapport, Prof. John Cartmill, Prof. Tarcisio Abreu Saurin, Prof Carlos Torres Formoso, Dr Emilie Francis-Auton, Miss Lieke Van Baar Ms Natália Ransolin.

This research meets the requirements set out in the National Statement on Ethical Conduct in Human Research 2007, (updated July 2018).

Standard Conditions of Approval:

1. Continuing compliance with the requirements of the National Statement, available from the following website: https://nhmrc.gov.au/about-us/publications/national-statement-ethical-conduct-human-research-2007-updated-2018.
2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports within three months of the anniversary of the approval for this protocol. You will be sent an automatic reminder email one week from the due date to remind you of your reporting responsibilities.
3. All adverse events, including unforeseen events, which might affect the continued ethical acceptability of the project, must be reported to the subcommittee within 72 hours.
4. All proposed changes to the project and associated documents must be submitted to the subcommittee for review and approval before implementation. Changes can be made via the Human Research Ethics Management System.

The HREC Terms of Reference and Standard Operating Procedures are available from the Research Services website: https://www.mq.edu.au/research/ethics-integrity-and-policies/ethics/human-ethics.

It is the responsibility of the Chief Investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Faculty Ethics Officer.

The Medicine & Health Sciences Subcommittee wishes you every success in your research.

Yours sincerely,

Dr Joel Fuller

Chair, Medicine & Health Sciences Subcommittee

The Faculty Ethics Subcommittees at Macquarie University operate in accordance with the National Statement on Ethical Conduct in Human Research 2007, (updated July 2018), [Section 5.2.22].

Page 1 of 1

APPENDIX C – Supplementary Material (Paper I)

SUPPLEMENTARY MATERIAL: detailed characterization of the selected papers Note: cells marked with an X indicate an association between the paper and the characterization criteria.																				
BIBLIOMETRIC INFORMATION			DESCRIPTION OF THE HEALTH SERVICE								STUDY FOCUS			DESIGN META-PRINCIPLES						
PAPERS (AUTHORS	COUNTRY	JOURNAL	OWNERSHIP		TEACHING OR NON-TEACHING SERVICES		SIZE			STUDY UNIT	OUTCOMES			Visibility		Design slack		Diversity of perspectives		WAD x WAI
							Small	Medium	Large					DESIGN PRINCIPLES						
			Public	Private	Teachin g	Non-teaching	Up to 50 beds	From 51 to 150 beds	151 to 500 beds		Safety	Well-being	Efficiency	Layouts that support resilience	Wayfinding	Flexibility same uses	Flexibility changing uses	Family/ patient perspec.	Staff perspec.	BEAD x BEAI
1 - Choi and Bosch, 2013	USA	HERD		x	x				x	Intensive Care Unit (ICU)		x					x	x		
2 - Karvonen et al., 2017	Finland	HERD	x		x				x	Non-clinical areas (routes)				x	x	x	x		x	
3 - Real, Bardach and Bardach, 2017	USA	Health Communication								Nursing Stations (Ward)	x	x	x	x	x		x	x	x	x
4 - France et al., 2009	USA	HERD		x	x				x	Neonatal Intensive Care Unit (NICU)		x	x	x	x	x	x	x	x	x
5 - Pati et al 2016	USA and EU	HERD		x	x				x	Emergency Department (ED)	x	x	x	x	x			x		x
6 - Naccarella et al 2019	Australia	HERD								ED		x	x	x		x	x	x	x	x
7- Apple 2014	Sweden	HERD								ICU		x	x	x	x	x	x		x	x
8 - Sundberg et al 2020	Sweden	Nursing in Critical Care								ICU	x	x			x	x				
9 - Blennerhassett et al 2018	Australia	HERD	x		x		x			Rehabilitation wards		x		x	x	x	x			
10 - Carmel-Gilfilen, Candy; Portillo, Margaret 2016	USA	HERD		x	x				x	Outpatient cancer care center		x		x	x	x	x			
11 - Lin et al 2016	Australia	Australian critical care: official journal of the Confederation of Australian	x		x				x	ICU	x		x				x	x	x	
12 - van Hoof et al 2015	Netherlands	Architectural Engineering and Design Management		x		x				Housing for people with dementia; The Zaandam Medical Centre		x								
13 - Baumgart et al 2009	Germany	Quality Management in Health Care			x					Operating Room (OR)	x		x	x			x	x	x	x
14 - Prugsiganont and Jensen, 2019	Thailand	Facilities	x	x	x				x	Public nonclinical areas (waiting areas, parking lots, restaurants, shops, cafés, hallways, staircases and elevators)		x	x	x	x		x	x		x
15 - Platt et al., 2017	**USA**	Journal of Interior Design			x					Veteran's Administration (VA) Acute Inpatient mental health (AIMH) Units	x	x		x	x	x	x	x		
16 - Copeland and Chambers, 2017	USA	HERD							x	Acute Care Units	x	x	x	x	x	x	x		x	x
17 - Machry et al., 2020	USA	HERD								Surgery centers	x	x	x	x	x	x	x			

SUPPLEMENTARY MATERIAL: detailed characterization of the selected papers
Note: cells marked with an X indicate an association between the paper and the characterization criteria.

BIBLIOMETRIC INFORMATION			DESCRIPTION OF THE HEALTH SERVICE								STUDY FOCUS			DESIGN META-PRINCIPLES						
PAPERS (AUTHORS	COUNTRY	JOURNAL	OWNERSHIP		TEACHING OR NON-TEACHING SERVICES		SIZE			STUDY UNIT	OUTCOMES			Visibility		Design slack		Diversity of perspectives		WAD x WAI
							Small	Medium	Large					DESIGN PRINCIPLES						
			Public	Private	Teachin g	Non-teaching	Up to 50 beds	From 51 to 150 beds	151 to 500 beds		Safety	Well-being	Efficiency	Layouts that support resilience	Wayfinding	Flexibility same uses	Flexibility changing uses	Family/ patient perspec.	Staff perspec.	BEAD x BEAI
18 -Plough et al., 2019	USA	HERD								Childbirth Facilities	x	x	x		x		x		x	x
19 - Rippin et al., 2015	USA	HERD			x				x	Neuro ICU	x	x	x				x	x	x	x
20 - Shultz et al., 2020	Canada	HERD							1	Universal OR	x	x	x							x
21 - Reno et al., 2014	USA	HERD	x	x	x	x	x		x	-		x	x				x	x		
22 - Holmdahl; Lanbeck, 2013	Sweden	HERD	x		x					Facility for infectious diseases (ID wards)	x	x	x	x	x	x	x	x		x
23 - Pati et al., 2012	USA	HERD						x	x	Surgical Units		x	x	x			x		x	x
24 - Schaumann et al., 2020	Israel	Facilities	x		x				x	Ward		x	x	x			x			
25 - Harte et al., 2016	Australia	HERD								Birth Unit		x		x	x	x	x	x		
26 - Fay et al., 2016	USA	HERD		x	x				x	ED	x	x		x	x				x	x
27. Jellema et al., 2020	Belgium	Building Research and Information			x	x			x	Cancer care facilities		x		x	x	x				
28. Bayramzadeh et al., 2018	USA	HERD							x	OR	x	x	x	x	x		x		x	x
29. Dehe and Bamford, 2017	UK	Production Planning and Control								Entire hospital		x	x	x	x	x	x			
30. Hui e Jun, 2019	USA	HERD			x				x	Surgical Department; Clinic; ED		x	x	x			x		x	
31. VanHeuvelen, 2019	USA	Sociology of Health & Illness							x	NICU	x	x	x	x					x	x
32. Rich and Day, 2008	USA	HERD								Ward		x	x	x	x	x		x	x	
33. Aalto et al., 2019	Finland	Engineering, Construction and Architectural Management								Entire hospital		x	x	x	x	x	x			
34. Rapport et al., 2020	Australia	BMC Health Services Research		x	x				x	Surgical Unit	x	x	x	x	x	x		x		x
35. Ransolin et al., 2020	Brazil	Applied Ergonomics	x		x				x	ICU	x	x	x	x	x	x		x		x
36. Pati et al., 2008	USA	Environment and Behavior		x	x	x		x	x	Surgical Units	x	x	x	x	x	x	x	x	x	x
37. Battisto e al., 2009	USA	The Journal of Nursing Administration (JONA)							x	Wards	x	x	x	x	x		x			x
38. Yi and Seo, 2012	USA	HERD			x					ICU		x	x	x			x			x
39. Sundberg et al., 2020	Sweden	HERD							x	ICU		x		x	x		x	x		
40 - Greer, et al., 2021	USA	HERD		x	x				x	Oncology Unit	x	x	x	x		x		x	x	x
41 - Waggener et al., 2021	USA	HERD		x	x				x	Surgical Unit	x	x	x	x	x				x	x

SUPPLEMENTARY MATERIAL: detailed characterization of the selected papers
Note: cells marked with an X indicate an association between the paper and the characterization criteria.

BIBLIOMETRIC INFORMATION			DESCRIPTION OF THE HEALTH SERVICE								STUDY FOCUS			DESIGN META-PRINCIPLES						
PAPERS (AUTHORS	COUNTRY	JOURNAL	OWNERSHIP		TEACHING OR NON-TEACHING SERVICES		SIZE			STUDY UNIT	OUTCOMES			Visibility		Design slack		Diversity of perspectives		WAD x WAI
							Small	Medium	Large					DESIGN PRINCIPLES						
			Public	Private	Teaching	Non-teaching	Up to 50 beds	From 51 to 150 beds	151 to 500 beds		Safety	Well-being	Efficiency	Layouts that support resilience	Wayfinding	Flexibility same uses	Flexibility changing uses	Family/ patient perspec.	Staff perspec.	BEAD x BEAI
42 - Pouyan et al., 2021	Iran	Journal of Building Engineering	x	x	x				x	All wards / Entire hospital		x		x	x					x
43 - Colman et al., 2020	USA	HERD							x	Wards and diagnostic and treatment (D&T) areas	x	x	x	x	x				x	

References - Supplementary Material (Paper I)

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APPENDIX D – Authorship statement (Paper I)

MACQUARIE University

MACQUARIE UNIVERSITY
AUTHORSHIP CONTRIBUTION STATEMENT

In accordance with the Macquarie University Code for the Responsible Conduct of Research and the Authorship Standard, researchers have a responsibility to their colleagues and the wider community to treat others fairly and with respect, to give credit where appropriate to those who have contributed to research.

Note for HDR students: *Where research papers are being included in a thesis, this template must be used to document the contribution of authors to each of the proposed or published research papers. The contribution of the candidate must be sufficient to justify inclusion of the paper in the thesis.*

1. DETAILS OF PUBLICATION & CORRESPONDING AUTHOR

Title of Publication (can be a holding title)		**Publication Status** Choose an item.
The Built Environment Influence on Resilient Healthcare: A SystematicLiterature Review		☐ In Progress or Unpublished work for thesis submission ☐ Submitted for Publication ☐ Accepted for Publication X Published
Name of **corresponding author**	Department/Faculty	**Publication details:** indicate the name of the journal/ conference/ publisher/other outlet
Natália Ransolin	AIHI/FMHHS and PPGCI/UFRGS	Health Environments Research &Design Journal (HERD)

2. STUDENTS DECLARATION (if applicable)

Name of HDR thesis author (If the same as corresponding author - write "as above")	Department/Faculty	Thesis title
as above	as above	Built environment knowledge for resilient performance in healthcare services
Description of HDR thesis author's contribution to planning, execution, and preparation of the work if there are multiple authors (for example, how much as a percent did you contribute to the conception of the project, the design of methodology or experimental protocol, data collection, analysis, drafting the manuscript, revising it critically for important intellectual content, etc.)		
NR and TS conceived the review. NR conducted the search and screened titles and abstracts. NR and CMZ read full texts and extracted data.NR undertook qualitative analysis and wrote the manuscript sections. TS revised the drafts during the manuscript development. FR, CTF, and RCW revised the paper's first and final draft. All authors approved the final version.		
I declare that the above is an accurate description of my contribution to this publication, and the contributions of other authors are as described below.	**Student signature** **Date**	[signature] 14/10/2023

Macquarie University **Authorship Contribution Statement** (November 2020)

MACQUARIE University

3. Description of all other author contributions

Use an Asterisk * to denote if the author is also a current student or HDR candidate.

The HDR candidate or corresponding author must, for each paper, list all authors and provide details of their role in the publication. Where possible, also provide a percentage estimate of the contribution made by each author.

Name and affiliation of author	Intellectual contribution(s) (for example to the: conception of the project, design of methodology/experimental protocol, data collection, analysis, drafting the manuscript, revising it critically for important intellectual content etc.)
Natália Ransolin, PPGCI/UFRGS and AIHI/MQ	Conceived the review; conducted the search and screened titles and abstracts; read full texts and extracted data; undertook qualitative analysis and wrote the manuscript sections; and approved the final version.
Tarcisio Abreu Saurin, PPGEP/UFRGS	Conceived the review; revised the drafts during the manuscript development; and approved the final version.
Caroline Melecardi Zani, University College London	Read full texts and extracted data and approved the final version.
Frances Rapport, AIHI/MQ	Revised the paper's first and final draft and approved the final version.
Carlos Torres Formoso, PPGCI/UFRGS	Revised the paper's first and final draft and approved the final version.
Robyn Clay-Williams, AIHI/MQ	Revised the paper's first and final draft and approved the final version.

4. Author Declarations

I agree to be named as one of the authors of this work, and confirm:

i. that I have met the authorship criteria set out in the Authorship Standard, *accompanying the* Macquarie University Research Code,

ii. that there are no other authors according to these criteria,

iii. that the description in Section 3 or 4 of my contribution(s) to this publication is accurate

iv. that I have agreed to the planned authorship order following the Authorship Standard

Name of author	Authorised * By Signature or refer to other written record of approval (eg. pdf of a signed agreement or an email record)	Date
Natália Ransolin	[signature]	21 Sep 2023
Tarcisio Abreu Saurin	[signature]	21 Set. 2023
Caroline Melecardi Zani	Carolina M Zani	21 Sep 2023
Frances Rapport	[signature]	04/10/2023
Carlos Torres Formoso	Documento assinado digitalmente gov.br CARLOS TORRES FORMOSO Data: 12/10/2023 09:27:56-0300 Verifique em https://validar.iti.gov.br	
Robyn Clay-Williams	[signature]	21 Sep 2023

5. Data storage

The original data for this project are stored in the following location, in accordance with the *Research Data Management Standard* accompanying the *Macquarie University Research Code*.

If the data have been or will be deposited in an online repository, provide the details here with any corresponding DOI.

Data description/format	Storage Location or DOI	Name of custodian if other than the corresponding author
Papers selected in the review and material for qualitative analysis; manuscript versions	Google Drive of the UFRGS student account (corresponding author)	

A copy of this form must be retained by the corresponding author and must accompany the thesis submitted for examination.

Macquarie University **Authorship Contribution Statement** (November 2020)

APPENDIX E – Supplementary Material (Paper II)

Supplementary Material: illustrations of uptake and neglect of practical examples, based on the case study

Design prescription: **Designing safe, efficient, and flexible routes between hospital units** (practical examples 1, 2, 3, 4, and 9)

1.

Walkway connecting the ICU and the in-patient wards, which are in separate buildings.

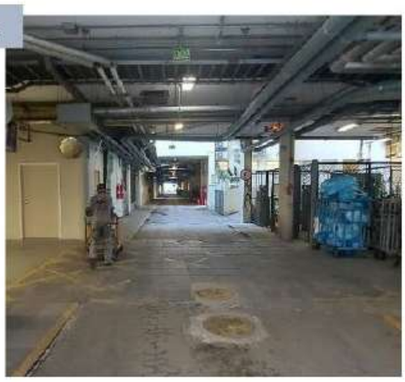
2.

Columns hindering the manoeuvring of the stretcher during the patient's transportation from ICU to radiology.

3.

Equipment hindering circulation in the ward corridors.

4.



Transportation route partly unroofed.

9.

Demarcations on the floor and walls for the route of the resuscitation team.

Design prescription: **Assess the pros and cons of centralisation versus decentralization of support areas that serve several hospital units** (practical example 13)

13

Left: terrace design with space for staff rest, mobilisation and physiotherapy for ICU patients; Right: leisure room (under construction) with artwork for staff.

Design prescription: **Giving visibility to flow interferences, obstacles, and risks that may compromise safety, efficiency, and flexibility** (practical examples 15, 20, 21, 24, and 27)

15.

Mirrors in the corridors' crossings to ensure the visualization of incoming flows.

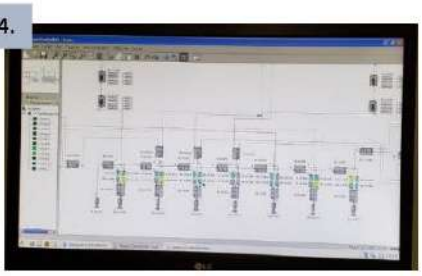
20.

Identification of ICU area and corresponding bed numbers.

21.

Dedicated elevators to COVID patients.

24.



Schematic plan cuts of the pneumatic tube system.

27.

Signalling risks of people falling and locking clothing chutes.

Design prescription: **Use visual management for the identification of spaces, resources, and processes** (practical examples 29, 32, and 34)

29.

Poster to inform staff about the change in the location of the pharmacy during the transition to the new building.

32.

Screenshot of the standardized routes to be followed by the cardiac arrest team.

34.

Floor plan with standardized routes hanging on the cleaning cart.

Design prescription: **Provide slack resources to cope with disruptions**
(practical examples 37, 39, 41, and 44)

37.

Newly installed spacious elevators for the transportation of patients and larger equipment.

39.

Narrow sidewalk.

41.

Large warehouse for the storage of equipment and supplies during the COVID-19 pandemic.

44.

Small room making it difficult to change the patient from the transportation stretcher to the radiology bed.

Design prescription: **Design for the prevention of infections and contamination**
(practical examples 46, 48 and 51)

46.

Schedule for family visits during the COVID-19 pandemic.

48.

Sink with liquid soap, paper towels and hand sanitizer at the ICU entrance.

51.

Coverage of the clothing cage.

Design prescription: **Use technologies supportive of safe, efficient, and flexible workflows**
(practical example 55 and 58)

55.

Tray with equipment (e.g., pumps, oxygen cylinders) that can be attached to the stretcher during patient transportation.

58.

Curved handrails/crash rails at one side wall in corridors where patients circulate.

APPENDIX F – Authorship statement (Paper II)

MACQUARIE UNIVERSITY
AUTHORSHIP CONTRIBUTION STATEMENT

MACQUARIE University

In accordance with the *Macquarie University Code for the Responsible Conduct of Research* and the *Authorship Standard*, researchers have a responsibility to their colleagues and the wider community to treat others fairly and with respect, to give credit where appropriate to those who have contributed to research.

Note for HDR students: *Where research papers are being included in a thesis, this template must be used to document the contribution of authors to each of the proposed or published research papers. The contribution of the candidate must be sufficient to justify inclusion of the paper in the thesis.*

1. DETAILS OF PUBLICATION & CORRESPONDING AUTHOR

Title of Publication (can be a holding title)		**Publication Status** Choose an item.
A knowledge framework for the design of built environment supportive of resilient internal logistics in hospitals		☐ In Progress or Unpublished work for thesis submission X Submitted for Publication ☐ Accepted for Publication ☐ Published
Name of **corresponding author**	Department/Faculty	**Publication details:** indicate the name of the journal/ conference/ publisher/other outlet
Natália Ransolin	AIHI/FMHHS and PPGCI/UFRGS	Journal of Applied Ergonomics

2. STUDENTS DECLARATION (if applicable)

Name of HDR thesis author (If the same as corresponding author - write "as above")	Department/Faculty	Thesis title
as above	as above	Built environment knowledge for resilient performance in healthcare services
Description of HDR thesis author's contribution to planning, execution, and preparation of the work if there are multiple authors (for example, how much as a percent did you contribute to the conception of the project, the design of methodology or experimental protocol, data collection, analysis, drafting the manuscript, revising it critically for important intellectual content, etc.)		
NR and TS conceived the study. NR wrote the study protocol amendment to include in the research project already approved by the Ethics and Research Committee of Hospital de Clínicas de Porto Alegre (HCPA)/ UFRGS. RCW, FR, and JC revised the study protocol versions. RCW assisted in Ethics submission. NR applied the study protocol for Ethics approval. NR conducted data collection, undertook the qualitative analysis, and wrote the manuscript sections. TS revised the drafts during the manuscript development. RCW, CTF, and FR revised the paper's first and final draft. All authors approved the final version.		
I declare that the above is an accurate description of my contribution to this publication, and the contributions of other authors are as described below.	**Student signature** **Date**	[signature] 14/10/2023

Macquarie University **Authorship Contribution Statement** (November 2020)

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University

3. Description of all other author contributions

Use an Asterisk * to denote if the author is also a current student or HDR candidate.

The HDR candidate or corresponding author must, for each paper, list all authors and provide details of their role in the publication. Where possible, also provide a percentage estimate of the contribution made by each author.

Name and affiliation of author	Intellectual contribution(s) (for example to the: conception of the project, design of methodology/experimental protocol, data collection, analysis, drafting the manuscript, revising it critically for important intellectual content etc.)
Natália Ransolin, PPGCI/UFRGS and AIHI/MQ	Conceived the study; conducted data collection, undertook the qualitative analysis, and wrote the manuscript sections; approved the final version.
Tarcisio Abreu Saurin, PPGEP/UFRGS	Conceived the study; revised the drafts during the manuscript development; approved the final version.
Robyn Clay-Williams, AIHI/MQ	Revised the paper's first and final draft and approved the final version.
Carlos Torres Formoso, PPGCI/UFRGS	Revised the paper's first and final draft and approved the final version.
Frances Rapport, AIHI/MQ	Revised the paper's first and final draft and approved the final version.

4. Author Declarations

I agree to be named as one of the authors of this work, and confirm:

i. *that I have met the authorship criteria set out in the* Authorship Standard, *accompanying the* Macquarie University Research Code,

ii. *that there are no other authors according to these criteria,*

iii. *that the description in Section 3 or 4 of my contribution(s) to this publication is accurate*

iv. *that I have agreed to the planned authorship order following the* Authorship Standard

Name of author	Authorised * By Signature or refer to other written record of approval (eg. pdf of a signed agreement or an email record)	Date
Natália Ransolin		21 Sep 2023
Tarcisio Abreu Saurin	Documento assinado digitalmente	
Robyn Clay-Williams	gov.br CARLOS TORRES FORMOSO Data: 12/10/2023 09:27:56-0300 Verifique em https://validar.iti.gov.br	ep 2023
Carlos Torres Formoso		
Frances Rapport		04/10/2023

5. Data storage

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If the data have been or will be deposited in an online repository, provide the details here with any corresponding DOI.

Data description/format	Storage Location or DOI	Name of custodian if other than the *corresponding author*
Transcripts of audio recordings and pictures of observations and interviews; manuscript versions	Google Drive of the UFRGS student account (corresponding author)	

A copy of this form must be retained by the corresponding author and must accompany the thesis submitted for examination.

Macquarie University **Authorship Contribution Statement** (November 2020)

APPENDIX G – Authorship statement (Paper III)

MACQUARIE University

MACQUARIE UNIVERSITY
AUTHORSHIP CONTRIBUTION STATEMENT

In accordance with the *Macquarie University Code for the Responsible Conduct of Research* and the *Authorship Standard*, researchers have a responsibility to their colleagues and the wider community to treat others fairly and with respect, to give credit where appropriate to those who have contributed to research.

Note for HDR students: *Where research papers are being included in a thesis, this template must be used to document the contribution of authors to each of the proposed or published research papers. The contribution of the candidate must be sufficient to justify inclusion of the paper in the thesis.*

1. DETAILS OF PUBLICATION & CORRESPONDING AUTHOR

Title of Publication (can be a holding title)		**Publication Status** Choose an item.
Beyond the operating room: how the built environment can support resilient performance within surgical services		☐ In Progress or Unpublished work for thesis submission X Submitted for Publication ☐ Accepted for Publication ☐ Published
Name of **corresponding author**	Department/Faculty	**Publication details:** indicate the name of the journal/ conference/ publisher/other outlet
Natália Ransolin	AIHI/FMHHS and PPGCI/UFRGS	Engineering, Construction and Architectural Management (ECAM)

2. STUDENTS DECLARATION (if applicable)

Name of HDR thesis author (If the same as corresponding author - write "as above")	Department/Faculty	Thesis title
as above	as above	Built environment knowledge for resilient performance in healthcare services
Description of HDR thesis author's contribution to planning, execution, and preparation of the work if there are multiple authors (for example, how much as a percent did you contribute to the conception of the project, the design of methodology or experimental protocol, data collection, analysis, drafting the manuscript, revising it critically for important intellectual content, etc.)		
NR, TS, and RCW conceived the study. NR wrote the study protocol. RCW, FR, and JC revised the study protocol versions. RCW assisted in Ethics submission. NR applied the study protocol for Ethics approval at Macquarie University Human Research Ethics Committee. JC assisted in recruiting participants. NR conducted data collection, undertook the qualitative analysis, and wrote the manuscript sections. TS revised the drafts during the manuscript development. RCW, CTF, FR, and JC revised the paper's final draft. All authors approved the final version.		
I declare that the above is an accurate description of my contribution to this publication, and the contributions of other authors are as described below.	**Student signature** **Date**	NRansolin 25/10/2023

Macquarie University **Authorship Contribution Statement** (November 2020)

MACQUARIE University

3. Description of all other author contributions

Use an Asterisk * to denote if the author is also a current student or HDR candidate.

The HDR candidate or corresponding author must, for each paper, list all authors and provide details of their role in the publication. Where possible, also provide a percentage estimate of the contribution made by each author.

Name and affiliation of author	Intellectual contribution(s) (for example to the: conception of the project, design of methodology/experimental protocol, data collection, analysis, drafting the manuscript, revising it critically for important intellectual content etc.)
Natália Ransolin, PPGCI/UFRGS and AIHI/MQ	Conceived the study; wrote the study protocol applied it for Ethics approval; conducted data collection, undertook the qualitative analysis, and wrote the manuscript sections; and approved the final version.
Tarcisio Abreu Saurin, PPGEP/UFRGS	Conceived the study; revised the drafts during the manuscript development; and approved the final version.
Robyn Clay-Williams, AIHI/MQ	Conceived the study; revised the study protocol versions; assisted in Ethics submission; revised the paper's final draft; and approved the final version.
Carlos Torres Formoso, PPGCI/UFRGS	Revised the paper's final draft and approved the final version.
Frances Rapport, AIHI/MQ	Revised the study protocol versions; revised the paper's final draft; and approved the final version.
John Cartmill, FMHHS/MQ	Revised the study protocol versions; assisted in recruiting participants; revised the paper's final draft; and approved the final version.

4. Author Declarations

I agree to be named as one of the authors of this work, and confirm:

i. *that I have met the authorship criteria set out in the* Authorship Standard, *accompanying the* Macquarie University Research Code,

ii. *that there are no other authors according to these criteria,*

iii. *that the description in Section 3 or 4 of my contribution(s) to this publication is accurate*

iv. *that I have agreed to the planned authorship order following the* Authorship Standard

Name of author	Authorised * By Signature or refer to other written record of approval (eg. pdf of a signed agreement or an email record)	Date
Natália Ransolin	[signature]	25/10/2023
Tarcisio Abreu Saurin	[signature]	25/10/2023
Robyn Clay-Williams	[signature] gov.br Documento assinado digitalmente CARLOS TORRES FORMOSO Data: 11/10/2023 06:55:24-0300 Verifique em https://validar.iti.gov.br	25/10/2023
Carlos Torres Formoso		25/10/2023
Frances Rapport	[signature]	25/10/2023
John Cartmill	[signature]	25/10/2023

5. Data storage

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If the data have been or will be deposited in an online repository, provide the details here with any corresponding DOI.

Data description/format	Storage Location or DOI	Name of custodian if other than the corresponding author
Transcripts of audio recordings and pictures of observations and interviews; manuscript versions	Sharepoint of the MQ student account (corresponding author)	

A copy of this form must be retained by the corresponding author and must accompany the thesis submitted for examination.

Macquarie University **Authorship Contribution Statement** (November 2020)

APPENDIX H – Publications during the candidature

Most of the work published during this candidacy is, to a great extent, related to the PhD topic. The citations marked with an asterisk (*) are those related to different research fronts, although grounded in the same theoretical foundations.

Prizes and awards

- The International Ergonomics Association (IEA)

Kingfar Award 2019 (PhD research)
US$1,000 for high-quality research in Human Factors and Ergonomics in developing countries (https://iea.cc/awards/iea-kingfar-award/)

- Resilience Engineering Association (REA)

Young Talents Program 2019 (Master Dissertation)
Workshop for ten selected Resilience Engineering post-graduation researchers from around the world to present and discuss their work with experts in the field. Financial support for travel and accommodation. (https://www.resilience-engineering-association.org/young-talents/).

Journal Papers

1. **Ransolin, N.**, Saurin, T. A., Clay-Williams, R., Formoso, C. T., & Rapport, F. (2024a). A knowledge framework for the design of built environment supportive of resilient internal logistics in hospitals. *Applied Ergonomics*, 116, 104209.
2. **Ransolin, N.**, Saurin, T. A., Clay-Williams, R., Formoso, C. T., Rapport, F., & Cartmill, J. (2024b). [Accepted for publication] Beyond the Operating Room: Built Knowledge Supportive of Resilient Surgical Services. *Engineering, Construction and Architectural Management (ECAM)*.
3. *Cheek, C., Hayba, N., Richardson, L., Austin, E. E., Auton, E. F., Safi, M., **Ransolin, N.**, ... & Clay-Williams, R. (2023). Experience-based codesign approach to improve care in Australian emergency departments for complex consumer cohorts: the MyED project protocol, Stages 1.1–1.3. *BMJ open*, *13*(7), e072908.
4. **Ransolin, N.**, Wachs, P., & Bueno, W. P. (2023). A functional perspective for Intensive Care Unit modelling. *Production*, *33*, e20220081.
5. **Ransolin, N.**, Saurin, T. A., Zani, C. M., Rapport, F., Formoso, C. T., & Clay-Williams, R. (2022). The Built Environment Influence on Resilient Healthcare: A Systematic Literature Review of Design Knowledge. *HERD: Health Environments Research & Design Journal*, *15*(3), 329-350.
6. *Bueno, W. P., Wachs, P., Saurin, T. A., **Ransolin, N.,** & de Souza Kuchenbecker, R. (2021). Making resilience explicit in FRAM: Shedding light on desired outcomes. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *31*(6), 579-597.
7. **Ransolin, N.**, Saurin, T. A., & Formoso, C. T. (2020). Integrated modelling of built environment and functional requirements: Implications for resilience. *Applied ergonomics*, *88*, 103154.

Book chapters

8. *Bertoni, V. B., **Ransolin, N.**, Wachs, P., & Righi, A. W. (2021, May). Resilience, safety and health: reflections about Covid-19'assistance. In *Congress of the International Ergonomics Association* (pp. 239-245). Cham: Springer International Publishing.
9. **Ransolin, N**., Saurin, T. A., & Formoso, C. T. (2021). 11 - Muddling Through the Built Environment to Preserve Patient Safety and Well-Being. *Resilient Health Care: Muddling Through with Purpose, Volume 6*, 109. Braithwaite, J., Hollnagel, E., & Hunte, G. (Eds.). CRC Press.

Conference proceedings

10. **Ransolin, N.** Saurin, T.A., Clay-Williams, R. Formoso, C.T., Rapport, F. Cartmill, J. Applying Built Environment Knowledge to improve Surgical Services. In: *National Conference of the Human Factors and Ergonomics Society of Australia (HFESA). Adelaide, Australia.* 19 - 22 November, 2023.
11. **Ransolin, N**., Saurin, T.A., Clay-Williams, R. Formoso, C.T., Rapport. The built environment knowledge for resilient performance in hospital internal logistics. (Poster). *EnCouRage Symposium*. Faculty of Medicine, Health and Human Sciences, Macquarie University. Sydney, 2023.
12. **Ransolin, N**., Saurin, T.A., Clay-Williams, R. Formoso, C.T., Rapport. Framework for the Built Environment supportive of Resilient Performance in the Connecting Areas of an Intensive Care Unit. In: *39th International Conference of the Society for Quality in Health Care (ISQua).* Seoul, Republic of Korea. 27 - 30 August, 2023.
13. **Ransolin, N**., Saurin, T.A., Clay-Williams, R. Formoso, C.T., Rapport, F. Cartmill, J. Built Environment Knowledge for Resilient Performance in a Surgical Service. Presented by: Clay-Williams, R. In: *The Resilient Health Care Society Summer Meeting (RCHS).* Florida, USA. 22 - 25 May, 2023.
14. **Ransolin, N.**, Zani, C. M., Saurin, T. A., Formoso, C. T., & Rapport, F. (2021, August). Does evidence-based design fit the complexity of healthcare services?: A systematic literature review. In *Resilient Health Care Society (RCHS): Virtual Scientific Meeting*.
15. *Formoso, C., Tommelein, I. D., Saurin, T. A., Koskela, L., Fireman, M., Barth, K., Bataglin, F., Viana, D., Coelho, R., Singh, V., Zani, C. M, **Ransolin, N.**, and Disconzi, C. (2021, July). Slack in Construction—Part 1: Core Concepts. In *Proceedings of the 29th Annual Conference of the International Group for Lean Construction, Lima, Peru*.
16. *Saurin, T. A., Viana, D. D., Formoso, C. T., Tommelein, I. D., Koskela, L., Fireman, M., Barth, K., Bataglin, F., Viana, D., Coelho, R., Singh, V., Zani, C. M, **Ransolin, N.**, and Disconzi, C. (2021, July). Slack in construction-Part 2: Practical applications. In *Proc. 29th Ann. Conf. Int. Group for Lean Construction, Lima, Peru*.
17. ***Ransolin, N.**, Gayer, B. D., Garcia, E. R., & Bertoni, V. B. (2021). Lean Production in a Manufacturing Unit: an Ergonomic View (Produção Enxuta em uma Unidade Manufatureira: uma Visão Ergonômica). In *ABERGO 2021 XXI Brazilian Congress of Ergonomics*. Even3 Publicações.

18. ***Ransolin, N.**, Marczyk, C. E. S., Gering, R. P., Saurin, T. A., & Formoso, C. T. (2021). Resilient healthcare during the COVID-19 pandemic: a case study in a Brazilian hospital. In *9th Symposium on Resilience Engineering*.

19. **Ransolin, N.**, Saurin, T. A., & Formoso, C. T. (2021). Modelling built environment requirements for resilient performance in healthcare facilities: a BIM and FRAM integrated approach. In *8th International Workshop When Social Science Meets Lean and BIM*.

20. ***Ransolin, N**., Marczyk, C. E. S., Gering, R. P., Saurin, T. A., Formoso, C. T., & Grøtan, T. O. (2021). The built environment's influence on resilience of healthcare services: lessons learnt from the COVID-19 pandemic. In *29th Annual Conference of the International Group for Lean Construction, IGLC 2021* (pp. 613-622). Department of Engineering, Civil Engineering Division, Pontificia Universidad Catolica del Peru.

21. **Ransolin, N**., Saurin, T. A., Formoso, C. T. (2020). Evidence-Based Design for Supporting Resilience in Healthcare Facilities. In: *28th Annual Conference of the International Group for Lean Construction (IGLC28) - PhD Summer School Book of Extended Abstracts.* 2020, Berkeley - Online.

22. **Ransolin, N.**, Saurin, T. A., & Formoso, C. T. (2020, September). The influence of the built environment on patient safety and wellbeing: A functional perspective. In *Proceedings of the 28th Annual Conference of the International Group for Lean Construction (IGLC28), Berkeley, CA: The International Group for Lean Construction. Retrieved* (Vol. 7).

23. **Ransolin, N.**, Saurin, T. A., & Formoso, C. T. (2019, June). Combining structural and functional modelling: exploring the relationship between the built environment and resilient healthcare. In *REA Symposium on Resilience Engineering Embracing Resilience*.

24. **Ransolin, N.** (2019, June). Functional and structural requirements in healthcare systems: a method for their integrated management. In *REA Symposium on Resilience Engineering Embracing Resilience*.

25. ***Ransolin, N**.; Pedó, B.; Conte, M.; Abegg, M. P.; Baldauf, J. P.; Formoso, C. T. Combining BIM, Lean and Agile Project Management in a Retrofit Building Project. In: *7th International Workshop When Social Science Meets Lean and BIM*. Florence, Italy, 2019.

26. *Bueno, W. P., Wachs, P., Saurin, T.A, **Ransolin, N.** Modelling Resilience Into The FRAM :insights from an ICU. In: *The 8th Resilient Health Care Meeting*. Osaka, Japão, 2019.

27. *Barth, K. B., Bazzan, J., **Ransolin, N.**, Formoso, C. T., & Echeveste, M. E. S. (2019). Performance measurement in lean production systems in the context of civil construction (Medição de desempenho em sistemas de produção lean no contexto da construção civil). In: *Simpósio Brasileiro de Gestão e Economia da Construção*, 11., 2019, Londrina. ANTAC.

Newsletters and Blog Posts

28. **Ransolin, N**. Designing and Operating the Built Environment for Resilient Healthcare Services. Sept 4, 2023. *Lean construction Blog*. Lean Design.

29. **Ransolin, N.** The Built Environment Influence On Resilient Healthcare. Feb 14, 2022. *Lean construction Blog.* Lean Design.

30. ***Ransolin, N.**; Bertoni, V. B. REA Newsletter Issue #10. REA Newsletter Latest News about Resilience Engineering Issue #10 November 2021.
31. ***Ransolin, N.**; Hegde, S. Towards a Definitive Guide to the Resilience Engineering Literature. REA Newsletter Latest News About Resilience Engineering Issue #6 September 2020.

APPENDIX I – Publication of Paper II

Applied Ergonomics 116 (2024) 104209

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Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

A knowledge framework for the design of built environment supportive of resilient internal logistics in hospitals

Natália Ransolin [a,b,1,*], Tarcisio Abreu Saurin [c], Robyn Clay-Williams [d], Carlos Torres Formoso [a], Frances Rapport [d]

[a] PPGCI/UFRGS (Construction Management and Infrastructure Post-Graduation Program, Federal University of Rio Grande do Sul), Av. Osvaldo Aranha, 99, Porto Alegre, RS, CEP 90035-190, Brazil

[b] AIHI/MQ (Australian Institute of Health Innovation, Macquarie University), Av. Osvaldo Aranha, 99, Porto Alegre, RS, CEP 90035-190, Brazil

[c] DEPROT/UFRGS (Industrial Engineering and Transportation Department, Federal University of Rio Grande do Sul), Av. Osvaldo Aranha, 99, Porto Alegre, RS, CEP 90035-190, Brazil

[d] AIHI/MQ (Australian Institute of Health Innovation, Macquarie University), 75 Talavera Rd, North Ryde, Sydney, NSW, 2113, Australia

A R T I C L E I N F O

Keywords:
Built environment
Design
Hospital logistics
Resilience

A B S T R A C T

Internal logistics is crucial for hospitals, occurring within facilities that pose constraints and opportunities, demanding resilient performance (RP) to adapt to dynamic conditions and balance safety and efficiency pressures. However, the role of the built environment (BE) to support RP is not explicitly analysed in the hospital logistics literature, which is usually limited to discuss BE in terms of layout and routing issues. To address this gap, this study presents a knowledge framework of BE supportive of RP in internal hospital logistics. The framework was developed based on a study in a large teaching hospital, encompassing 11 service flows of people and supplies between an intensive care unit and other units. Data collection was based on 38 interviews, documents such as floor plans, and observations of logistics activities. Seven BE design principles developed in a previous study, concerned with RP in general but not focused on logistics, were adopted as initial themes for data analysis. Results of the thematic analysis gave rise to a knowledge framework composed of seven design prescriptions and 63 practical examples of BE supportive of RP in hospital internal logistics. The paper discusses how these prescriptions and examples are connected to resilience management. The framework is new in the context of internal hospital logistics and offers guidance to both BE and logistics designers.

1. Introduction

Health services have long been acknowledged as complex systems that display a myriad of manifestations of resilient performance (RP) (Braithwaite, 2018), defined as the expression of how systems cope with both expected and unexpected conditions while maintaining the delivery of the required outputs (Hollnagel, 2017). RP is an emergent property arising from the dynamic interactions between diverse technical, social, and organizational elements of health services, which are subject to the influence of the external environment (Wachs et al., 2016). The built environment (BE) is a key technical element of most health services, as it has a strong impact on the service efficiency, safety, and resilience (Machry et al., 2021). This paper is concerned with RP that stems from the interactions between people and the BE of hospitals, which comprises the physical assets such as buildings, utilities, furniture, and signage. The BE role in the RP of health services has been investigated mostly in the realm of coping with natural or man-made disasters (Keenan, 2020; Ochi et al., 2020). However, RP is also necessary and present during everyday work, once resilient health services should monitor, anticipate, respond, and learn from both expected and unexpected variability (Hollnagel, 2017).

Earlier studies of BE and RP in health services, however, pay little heed to the internal logistics of hospitals, defined as the functions of purchasing, moving, catering, handling, and storage of physical entities

* Corresponding author. PPGCI/UFRGS (Construction Management and Infrastructure Post-Graduation Program, Federal University of Rio Grande do Sul), Av. Osvaldo Aranha, 99, Porto Alegre, RS, CEP 90035-190, Brazil.

E-mail addresses: nransolin@gmail.com (N. Ransolin), saurin@ufrgs.br (T.A. Saurin), robyn.clay-williams@mq.edu.au (R. Clay-Williams), formoso@ufrgs.br (C.T. Formoso), frances.rapport@mq.edu.au (F. Rapport).

[1] Present address: 75 Talavera Rd, North Ryde NSW 2113, Australia, Sydney.

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Table 1
Principles for the design of BE supportive of RP – based on Ransolin et al. (2022).

	Design principles	Description
1	Designing layouts that support RP	BE configurations that improve the efficiency of operations and support users' safety, well-being and interactions.
2	Supporting wayfinding	Support to the orientation and navigation of users across BE in health services.
3	Providing flexibility while maintaining the same functionality	BE attributes that allow adaptation, customization, and expansion, while maintaining the main purpose of spaces.
4	Providing flexibility for changing functionalities	BE attributes that allow adaptation, customization, and expansion, aiming at completely new purpose for spaces
5	Leveraging patient and family perspectives	Consideration of the perspectives of family members in the BE design.
6	Leveraging staff perspectives	Consideration of the staff perspectives in the BE design.
7	Reconciling the gap between the built environment-as-done (BEAD) and the built environment-as-imagined (BEAI)	BE design (i.e., BEAI) strongly based on the understanding of how people use the BE in reality (BEAD).

Table 2
Sources of evidence and their association with the stages of the case study.

Stages of the case study	Sources of evidence			
	Semi-structured interviews	Non-participant observations	Meeting with hospital staff to discuss the final results	Document analysis
1 – Selection and characterization of the service flows and their BE	x	x		x
2 – Development of the knowledge framework for the design of BE supportive of RP in internal logistics	x	x	x	x
Total (hours)	**30** **81**	**50**	**1**	-

such as materials, equipment, and people (Jawab et al., 2018; Moons et al., 2019). Several requirements must be fulfilled by those functions, such as to use the shortest possible routes between suppliers and customers, to follow standardized routines to the possible extent, and to deliver according to customers' demands (Moons et al., 2019; Volland et al., 2017).

This research study focuses on the logistics functions that take place in the areas that connect the hospital units such as corridors, elevators, stairways, accesses in general, and other common areas. Despite its importance, the role of the BE is not explicitly addressed in the hospital logistics literature, although it is implicit in the discussion of layout and routing (Prugsiganont and Jensen, 2019). This is a narrow perspective that does not account for the complex activities that occur in the connecting areas (Machry et al., 2022). For instance, these areas can be turned into clinical workspaces due to necessity – e.g., they may be used as waiting areas for patients before exams, and critically-ill patients may need care during their transportation (Copeland and Chambers, 2017). Further, similar to other activities in health services, those related to internal logistics display RP due to variabilities that challenge the standardized operating procedures – e.g., the standard routes may be blocked, there may be sudden surges of demand, or signage may be

Table 3
- Interviewees, their jobs, and duration of the interviews. Notes: interviewees and groups marked with * are professionals from hospital units other than the ICU; interviews marked with ** occurred in groups.

Interviewees		Duration of the interviews (h)
Type	Number of interviewees and job	
Hospital quality management staff	1 medical doctor*	2**
	1 nurse*	
	1 industrial engineer*	
Administrative staff	2 hospitality service managers*	
	3 ICU managers	6
	1 ICU pharmacy manager	1
	1 central pharmacy and warehouse manager*	1
	4 ward pharmacy manager*	2
	1 hospital dietary service manager*	1.5
	1 hospital cleaning manager*	2.5
	2 hospital clothing managers*	4
	2 hospital waste managers*	1
Engineering	1 architect*	1.5
	1 maintenance worker (mechanical)*	1
Clinical assistance	1 ICU medical-chief	1
	2 ICU doctors	2
	1 radiologist*	1
	1 ICU nursing-chief	1
Clients	1 patient	1.5**
	2 family members	
Total	**38 interviewees**	**30 h**

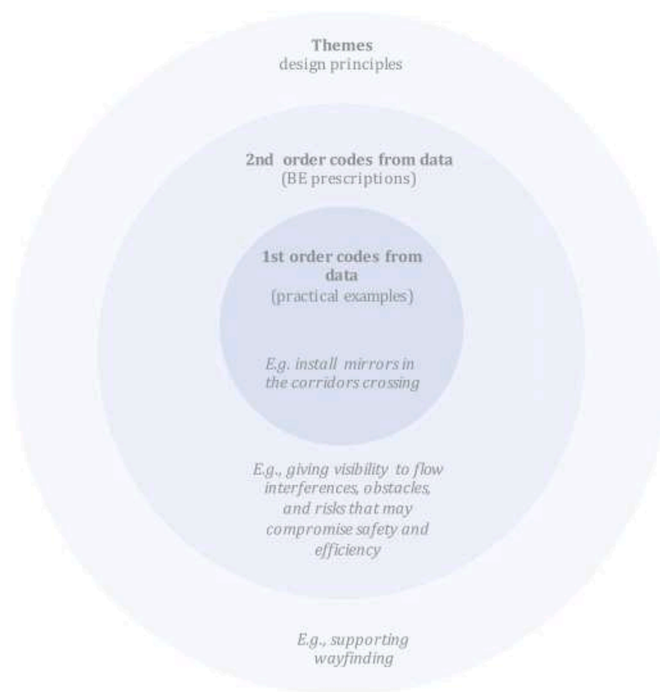

Fig. 1. Coding process.

outdated (Capolongo et al., 2020). Nevertheless, both in healthcare and other sectors, the literature stresses RP in the external logistics, related to what occurs in-between the supplier and client facilities (Komljenovic, 2021). This is understandable as external logistics are vulnerable to high-profile events (e.g., strikes, natural disasters, pandemics) that simultaneously affect a large number of companies (Ivanov, 2021).

Therefore, it is important to understand how the BE influences RP in the connecting areas of hospitals where internal logistics takes place.

Fig. 2. Left: corridors at the entrance to the ICU; middle: sidewalks at the underground; right: roads at the underground.

Fig. 3. Left: elevator that connects the main hospital warehouse to the ICU pharmacy; right: pneumatic tube and capsules for placing materials.

Against this background, the research question addressed by this paper is stated as follows: how to develop design knowledge that supports RP of internal logistics in hospitals? The point of departure for addressing this question is the knowledge framework for the design of BE supportive of RP in health services in general, developed by Ransolin et al. (2022). However, that framework was derived from a literature review of studies focused on clinical units (e.g., wards, operating theatres), paying scant attention to the common hospital areas (e.g., corridors, storage areas). The activities that occur in these common areas are mostly related to internal logistics (e.g., transportation and storage of supplies, often over fairly long distances) and therefore substantially differ from those at the clinical units (e.g., direct patient care, exams, and preparation of medications). Therefore, the research aim is to refine the framework developed by Ransolin et al. (2022), making it tailored to the BE associated with internal logistics. The refined framework is new and expected to be useful to both BE and logistics designers.

The research question was empirically investigated in the areas that connect intensive care units (ICUs) to other hospital units, hereafter referred to as c-ICU areas, in a large teaching hospital from Brazil. ICUs were chosen because of their complex interactions with other hospital units (Bueno et al., 2019), demanding resilient internal logistics. The study of the c-ICU areas and logistics gave rise to a knowledge framework composed of design principles, design prescriptions, and practical examples of how the BE might support the RP of internal logistics in hospitals. The term *design prescription* refers to suggestions for action in a given circumstance to achieve an effect (Vaishnavi and Kuechler, 2015). The term *practical example* refers to an instantiation of the prescription in a real, specific setting. The term *principles*, as used by Ransolin et al. (2022), refers to sets of prescriptions that share similar goals, signifying a higher abstraction than prescriptions and examples.

2. Background

2.1. Resilient performance and the built environment

In healthcare facilities, the activities that make up the service flows are not always properly understood by designers, resulting in unfit-for-purpose spaces (Lacanna et al., 2019; Rapport et al., 2020). This drawback results in a wide gap between work-as-imagined (WAI) in design and protocols and work-as-done (WAD) in practice (Borsci et al., 2018).

Resilience engineering can be used to understand this gap, providing visibility to RP that fills out the under specification of design (Hollnagel, 2012). RP arises partly from the informal self-organization of people and partly from deliberate design decisions intended to support it. This latter portion is associated with the concept of Design for Resilient Performance, defined as “the use of design principles to support integrated human, technical, and organizational adaptive capabilities” (Disconzi and Saurin, 2022). Ransolin et al. (2022) conducted a systematic literature review and proposed a knowledge framework composed of seven principles, 21 prescriptions, and 58 practical examples of BE design decisions that support RP in health services. The seven design principles are presented in Table 1.

2.2. Built environment and internal logistics in hospitals

Black and Miller (2008) group the activities of hospitals’ internal logistics into seven flows, related to: patients, family, providers, medication, supplies, information, and equipment. The patient flow takes a central stage, and thus all other flows should serve it, bridging organizational silos that usually exist in hospitals (Moons et al., 2019).

Logistics within hospitals is often constrained by the BE, which influences, for example, the choice of routes and transportation equipment, walking distances, and elevator use (Cubukcuoglu et al., 2021).

Table 4
Selected service flows from and to the ICU.

Hospital units that interact with the ICU	**Selected service flows**											**Total**
	People					**Supplies**						
	RS	**EX**	**AD**	**DH**	**VI**	**D/M**	**DI**	**SM**	**CL**	**CH**	**WA**	
Central pharmacy and Warehouse						**X** **205m** (S:124m + C:57m + E:24m or WE:24m) **Or 24m** (PT)						1
Clothing										**X** **290m** (R:174m + C:92m + E:24m)		1
Cleaning									**X** **126m** (S:34m + C:92m + E:24m)			1
Waste management											**X** **205m** (R:205m + C: 92m + E:24m)	1
Reception desk					**X** **152m** (C:129m + E:23m)							1
Emergency department	**X** **170m** (C:147m + E:23m)	**X** **250m** (C:245m + E:5m)	**X** **170m** (C:147m + E:23m)									3
Kitchen							**X** **270m** (C:247m + E:23m)					1
Radiology	**X** **285m** (C:267m + E:18m)	**X** **240m** (C:22m+ E:18m)										2
Laboratory		**X** **18m** (PT)										1
Ward	**X** **124m** (C)			**X** **124m** (C)								2
Surgical unit	**X** **134m** (C:126m + E:8m)		**X** **134m** (C:126m + E:8m)									2
Sterilized materials centre								**X** **54m** (C:50m + E:4m) **Or 4m** (WE/PT)				1
Ward pharmacy						**X** **128m** (C:116m + E:12m) **Or 12m** (PT)						1
Total 1	**713m**	**508m**	**304m**	**124m**	**152m**	**333m**	**270m**	**54m**	**126m**	**291m**	**205m**	-
Legend												
	Horizontal distances: Corridors (**C**); Sidewalks (**S**); Roads (**R**) **Vertical distances:** Elevators (**E**); Pneumatic Tube (**PT**); Warehouse Elevator (**WE**)											
	Patient: Resuscitation (**RS**); Exams (Radiology/Laboratory) (**EX**); Admission (**AD**); Discharge (**DH**) **Family**: family members and visitors (**VI**)											
	Supplies: Drugs and Medical Materials (**D/M**); Dietary (**DI**); Sterilized Materials (**SM**); Cleaning (**CL**); Clothing (**CH**); Waste (**WA**)											

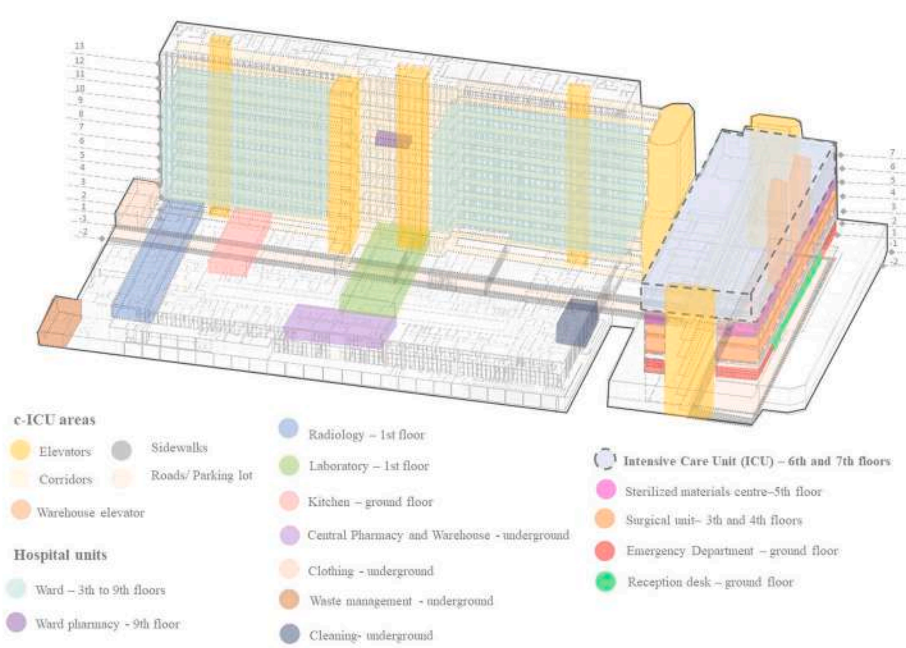

Fig. 4. Hospital units, c-ICU areas, and service flows.

Table 5
Practical examples associated with the BE design prescription "designing safe, efficient, and flexible routes between hospital units".

Designing safe, efficient, and flexible routes between hospital units	People					Supplies					
Flows / Practical examples	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
1. Creating direct connections between hospital units located in different buildings (e.g., walkways in all floors). This prevents inter-building transit only through the ground floor. (O)	X	X	X	X	X	X	X	X	X	X	X
2. Positioning columns to free up space for manoeuvring of trolleys, stretchers, and other equipment. (O, I)	X	X	X	X		X	X	X	X	X	X
3. Placing workstations for professionals in the corridors in such a way that this does not compromise the minimum free width of corridors set by regulations (e.g., corridors must have a minimum width of 2.0 m when they are longer than 1.10 m, and 1.20 m otherwise). (O, R)	X	X	X	X		X	X	X	X	X	X
4. Adopt roofed supply transportation paths as a protection against inclement weather. (O, I)						X	X	X	X	X	X
5. Design easy-to-use and standard device in elevators (e.g., key or card) to allow for a non-stop journey to the desired floor. This can be crucial, for example, for the resuscitation team when attending a cardiac arrest. (O, I, R)	X	X				X					
6. Designing standardized routes for waste collection from hospital units. (O, I)											X
7. Avoiding curves in the pneumatic tube pipes so as not to damage nor block the load. (I)						X					
8. Locating origin and destination areas adjacent to each other to minimize the transportation of critical patients (e.g., place post-operative beds inside the ICU). (O, I)			X								
9. Reviewing route to the unit that requested cardiac arrest assistance before leaving the ICU. Standardized routes should not be taken for granted as they may be blocked due to changes in spaces and processes. Additionally, a nurse technician can be allocated to leave earlier and free the routes (e.g., fire doors are often heavy and difficult to handle in an emergency), and provide key cards for resuscitation team members to access all hospital environments. (O, I)	X										
Total of practical examples per flow	5	4	4	3	1	6	4	4	4	4	5

Past studies have explored these implications mostly from the viewpoint of routing and layout. For instance, the proper location of the clinical units allied with a levelled traffic contribute to decrease congestion and transportation times among hospital areas (Cubukcuoglu et al., 2021). Further, departments' adjacency must match operational processes to avoid transportation waste - e.g., support and care units should be close to each other (Karvonen et al., 2017). There are also consequences to patient safety as long transportations contribute to complications in patient's conditions (Ulrich and Zhu, 2007). Thus, it is important to avert constraints such as bumps on the floor, waiting for elevators, and lack of power outlets in the corridors (Ransolin et al., 2020; Ulrich and Zhu, 2007). Storage of equipment (e.g., wheelchairs, bed, connectors), and furniture (e.g., tables, chairs, storage cabinets) can also block staff and patient routes (Bayramzadeh et al., 2018; Battisto et al., 2009). Copeland and Chambers (2017) and Prugsiganont and Jensen (2019) described the efforts made by staff to navigate through obstacles and distractions related to the BE during the transportation of patients between units.

These examples indicate that the relationship between BE and internal hospital logistics is non-trivial. The understanding of these relationships can benefit from the modelling of the connections between logistics functions and BE. For this purpose, a possible approach is through using the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012). In FRAM, a function corresponds to the activities required to produce a certain outcome (Hollnagel, 2012). Ransolin et al. (2020) used the FRAM for modelling the connections between functions in an ICU (e.g., patient discharge, drug administration) and the corresponding BE requirements, considering these as preconditions for the functions. Hollnagel (2012) defines preconditions as "conditions that must be exist before a function can be carried out". The use of 3D representations of the BE and simulation of the workflows (Halawa et al., 2020) can also support the joint modelling of BE and activities of internal logistics.

3. Research method

3.1. Research design

To address the research question, we conducted a case study of how the BE influenced the RP of the internal logistics in a hospital, emphasizing the c-ICU areas. The case study approach was chosen as it offers exploratory insight into social-technical phenomena in real-world settings (Flyvbjerg, 2011). This fits the nature of this research as the relationship between the BE and hospital internal logistics is an under explored topic of socio-technical nature. Moreover, case studies set a basis for the bottom-up, inductive development of propositions –

Table 6
Practical examples associated with the BE design prescription “assess the pros and cons of centralisation versus decentralisation of support areas that serve several hospital units”.

Assess the pros and cons of centralisation versus decentralisation of support areas that serve several hospital units											
Flows	**People**					**Supplies**					
	Resuscitation	**Exams**	**Admission**	**Discharge**	**Visitors**	**Drugs and Medical Materials**	**Dietary**	**Sterilized Materials**	**Cleaning**	**Clothing**	**Waste**
Practical examples	**10.** Designing supporting areas, such as clothing and exam hubs (e.g., for gowns and radiology service) that serve more than one hospital unit, avoiding replication of resources. (O, I, R)										
	X	X	X	X	X	X	X	X	X	X	X
	11. Sharing expensive and scarce equipment or infrastructure (e.g., tomography, defibrillators, crash carts, pharmacy) between ICUs and other hospital units. (O, I)										
	X	X	X	X		X		X			
	12. Designing decentralised supporting rooms (e.g., deposits of materials and waste) to reduce movement of staff. (O, I)										
						X		X	X		
	13. Designing rest and green areas with stimulating colours, furniture, decoration, and art to be used by several hospital units (e.g., terraces and patios with space for mobilisation and physiotherapy). (O, I)										
			X		X						
	14. In cases where supporting rooms are decentralised, waste collection routes might be more effectively arranged according to building plans (e.g., east-west or north-south). (I)										
											X
	Total of practical examples per flow										
	2	**2**	**3**	**2**	**2**	**3**	**1**	**3**	**2**	**1**	**2**

theories – that explain the patterns identified in the data (Woo et al., 2017). In this research study, these propositions correspond to the contents of the devised knowledge framework for the design of BE supportive of RP in internal logistics.

The selection of a relevant case is crucial for external validity. As such, we chose a large (around 6000 employees) public, teaching, and tertiary hospital in Southern Brazil. We focused on the interactions between a 95-bed adult ICU and other hospital units. These units encompass clinical (e.g., in-patient wards) and non-clinical areas (e.g., pharmacy). There were several logistics activities that took place across a three-building complex, which has around 223,000 square meters. This setting was expected to produce rich data, offering insight into the research question. Furthermore, the ICU had recently been installed in a newly built area, and the interactions with the other hospital units had not yet been completely designed and tested. Thus, ICU managers were interested in this study as its results could be applied to new workflows.

For internal validity, we followed established best practice of case-based research, namely: development of data collection protocols (Eisenhardt and Graebner, 2007); triangulation of data and data sources (Noor, 2008); development of a database, allowing traceability and reinterpretation of data when necessary (Flyvbjerg, 2011); use of visual representations to illustrate the contributions of the study (Eisenhardt and Graebner, 2007); and presentation of the results to the participants of the case study, to obtain their feedback (Rapport et al., 2018). The case study had two stages:

(i) Selection and characterization of the service flows and their BE: the selection of flows to be investigated was made in a meeting with the ICU administrative manager (4 years of experience at the ICU). This manager pointed out the main flows of people and supplies to and from the ICU, from the viewpoints of safety and efficiency. Then, the flows were characterized based on their most salient socio-technical characteristics such as distances, equipment, and people involved; and

(ii) Development of the knowledge framework for the design of BE supportive of RP in internal logistics: this stage was concerned with the identification of instances of BE implications to internal hospital logistics, emphasizing situations that demanded RP.

3.2. Data collection

Data collection was carried out by the first author, who had been involved in a previous research project on BE and resilience engineering at the old ICU of the same hospital (Ransolin et al., 2020). This experience facilitated understanding the ICU processes and access to the sources of data. The hospital’s ethics committee approved this research project, and hospital representatives who participated in the study provided written informed consent before being interviewed. Table 2 shows the sources of evidence used in each stage of the case study, resulting in a total of 81 h of data collection.

Semi-structured interviews were carried out with 38 hospital representatives listed in Table 3. Altogether, 26 interviews were conducted, some of them in small groups either for the convenience of the interviewees or because they worked in close collaboration with each other. Thirteen interviewees were professionals from other hospital units which had relevant interactions with the ICU.

Interviews were audio-recorded and two questions were asked: (1) could you give an overview of the functioning of this unit and its corresponding service flows related to the ICU? Please emphasize the role of the BE environment; and (2) how does the BE facilitate or hinder everyday work regarding the ICU service flows? Patients and family members were only asked to report their perceptions on the BE in the c-ICU areas.

Non-participant observations (50 h) occurred over 32 visits to the hospital. This observation type is unstructured, recommended to qualitative and context-driven studies; the researcher watches the subjects of their study, with their knowledge, but without taking an active part in the situation under scrutiny (Scott and Marshall, 2009). Considering this study’s interest in understanding logistics activities and their relation

Table 7
Practical examples associated with the BE design prescription “giving visibility to flow interferences, obstacles, and risks that may compromise safety, efficiency, and flexibility”.

Giving visibility to flow interferences, obstacles, and risks that may compromise safety, efficiency, and flexibility											
Flows	People					Supplies					
Practical examples	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
15. Installing mirrors in the corridors’ crossings to ensure the visualization of incoming flows. (O)	■	■	■	■	■	■	■	■	■	■	■
16. Balancing concerns with ease of access during emergencies (e.g.,in case of fire; the resuscitation team needs to quickly unlock doors; electronically controlled doors may hamper the access for cleaning staff) and access restrictions due to security requirements (e.g., psychiatric patients may try to escape). (O, I, R)	■	■	■	■	■	■	■	■	■	■	■
17. Designing places to store dirty clothes separately from the storage of clean clothes. (O, I)						■	■	■	■	■	■
18. Using colours to identify laundry cage covers according to the service flow (e.g., yellow for clean clothes distribution and blue for collection of dirty clothes). (O, I)						■	■	■	■	■	■
19. Allocating a signalized area for parking supply carts and unloading materials near the ICU pharmacy. (O)						■	■	■	■	■	■
20. Including information about bed numbers on directional signs in the corridors to facilitate patient search in the ICU. (O, I)	■	■	■	■	■						
21. Using dedicated elevators for patients to avoid flow interferences. (O, I, R)	■	■	■	■	■						
22. Making key information on patient condition available for consultation by professionals during intra-hospital patient transportation (e.g., signal the decision on the resuscitation condition of patients on the bed). (O, I)	■	■	■								
23. The doors of all rooms where large equipment is installed should be large enough or have removable panels. (O, I, R)		■	■	■							
24. Providing detailed plan cuts of the pneumatic tube system, for troubleshooting (e.g., coping with stuck capsules or tube maintenance). (O, I)		■				■					
25. Incorporating a system (e.g., doorbell/audible alarm/phone ring) to announce that the resuscitation team is arriving, to clear the way and be prepared. (O, I)	■										
26. Allocating a signalized place for parking one of the crash carts just outside of the ICU preventing access of external people who may need this equipment. (O, I)	■										
27. Signalling risks of people falling and locking out all chutes, using them for one purpose only (e.g., do not use the same chute for dirty clothes and waste collection). (I, R)			■	■	■					■	■
28. Designing a parking area for the clothing cages just outside the clothing unit or in the pathway to the hospital units to be supplied. This releases space in the clothing unit and speeds up transportation. (O, I)										■	
Total of practical examples per flow	**7**	**7**	**7**	**6**	**5**	**6**	**5**	**5**	**5**	**7**	**6**

with the BE, the observations focused on: activities performed by frontline workers in the c-ICU areas; walkthrough sessions in which staff involved in workflows guided the main researcher through the c-ICU areas, explaining the logistics activities and the BE where they occurred; staff meetings to discuss adjustments and pending issues in the BE as the ICU had been recently installed; and one training session for the ICU-based team in charge of resuscitation in all units of the hospital – this was one of the selected workflows. Notes from observations were recorded on a diary on the same day or on the day following the hospital visits. Interviews and observations were discontinued when saturation was perceived to have occurred, which means that findings started being repetitive and the data collected was regarded by the researchers as sufficient for the purpose of addressing the research goals (Ritchie et al., 2003).

Document analysis involved the Brazilian regulation RDC-50 (Anvisa – Agência Nacional de Vigilância Sanitária, 2002), which defined some BE requirements for the c-ICU areas. Thus, the analysis of regulations focused on requirements for areas such as corridors, elevators, and doors, rather than areas primarily dedicated to clinical care. Moreover, a building information model (BIM) previously developed by Ransolin et al. (2020) for the same hospital, using the software *Autodesk Revit Architecture*, was consulted as it contained architectural floor plans

Table 8
Practical examples associated with the BE design prescription “use visual management for the identification of spaces, resources, and processes”.

Use visual management for the identification of spaces, resources, and processes	People					Supplies					
Flows	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
Practical Examples											
29. Using signage such as stickers and posters to increase awareness of temporary changes in flows and spaces (e.g., identification of dedicated COVID-19 patient transport elevator). (O, I)	■	■	■	■	■	■	■	■	■	■	■
30. Designing self-explanatory direction signage for hospital flows and areas (e.g., use of colours and symbols), including hospital entrances and exits. (O, I, R)	■	■	■	■	■	■	■	■	■	■	■
31. Communicating the resuscitation team telephone number in corridors and other hospital common areas. (O, I)	■										
32. Hanging maps on the crash cart to help the resuscitation team identify the routes for each hospital unit. (O, I)	■										
33. Designing an intuitive numbering system to identify the hospital units. (O)						■					
34. Creating posters with spreadsheets detailing the routes (e.g., elevators, corridors, and rooms to access) with schedules, types, and amounts of waste to be removed. (O, I)											■
35. Tagging the hamper before shipping it down to the chutes and cages. (O, I)										■	
Total of practical examples per flow	**4**	**2**	**2**	**2**	**2**	**3**	**2**	**2**	**2**	**3**	**3**

and a 3D model of the hospital complex.

There was also a **meeting with hospital staff** (1 h) to present the design knowledge framework in an online environment. The audience consisted of seven professionals from the administrative staff, engineering, and clinical assistance. All of them had been interviewed during data collection. The main researcher presented each element that formed the knowledge framework, along with images from the hospital. Participants were asked to provide feedback on the clarity and applicability of the material presented.

3.3. Data analysis

Data from all sources of evidence were subject to a thematic analysis following the steps recommended by Pope et al. (2000): familiarization, identifying themes, coding, charting, and mapping and interpretation. To comply with ethics and privacy guidelines, empirical data were de-identified and saved in an online educational institution storage. For familiarization, the primary coders (NR and TAS), both experienced human factors and resilience engineering researchers, read several times the relevant regulations, the verbatim transcripts from the interviews, and notes from observations, which jointly accounted for about 15,000 words. Next, an a priori structure, corresponding to the seven design principles by Ransolin et al. (2022) presented in Table 1, was selected to define the initial themes.

Following, data were coded by NR and TAS independently in accordance with the initial themes. Such coding involved the triangulation of sections of text from all data capture approaches that were related to the same themes, embellishing one another.

These authors had three meetings to discuss disagreements, achieve coding consensus, and maximise rigour. For the purpose of assessing face validity, the three other authors (RCW, CTF, and FR) later reviewed the consensual coding from NR and TAS, suggesting minor adjustments. The coding process occurred according to different levels of abstraction, referred to as 1st and 2nd order coding (Fig. 1). First order coding, the lowest abstraction level, was carried out deductively and involved the identification of excerpts of text associated with the seven design principles. For instance, the following remark by the manager of the resuscitation team was associated with the design principle ‘supporting wayfinding’: “*we have mirrors at the intersections between corridors to see when someone is coming in our direction; this helps to prevent collisions with stretchers or equipment*”. These excerpts, 1st order codes, gave rise to the first and lowest level of the proposed knowledge framework. This level is hereafter referred to as practical examples of BE supportive of RP in internal hospital logistics. For the aforementioned excerpt, the example was worded as “install mirrors at the corridor crossings”.

Next, 2nd order coding was conducted inductively, giving rise to design prescriptions that encompassed several examples that were grouped according to a similar core purpose. For instance, the aforementioned example was grouped with others that were similar, to generate the prescription “giving visibility to flow interferences, obstacles, and risks that may compromise safety and efficiency”. Note that a prescription can have emerged from several principles, rather than existing a one-to-one relationship between principles and prescriptions. The thematic analysis continued with the charting stage, which schematically represented the framework. Finally, at the mapping and interpretation stage, results were discussed in light of resilience engineering and logistics theoretical background.

4. Results

4.1. Selection and characterization of the service flows and their built environment

The ICU has 95 individual patient rooms arranged in 10 pods, nine of them with ten beds each and another with five beds. A standard room accommodates approximately 30 items of equipment, furniture, and

Table 9
Practical examples associated with the BE design prescription “plan slack resources to cope with disruptions”.

Provide slack resources to cope with disruptions	People					Supplies					
Flows / Practical examples	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
36. Providing elevators with a "no break" device, with a substantial autonomy (e.g., one hour) in the event of a power shortage. (R)	X	X	X	X	X	X	X	X	X	X	X
37. Designing more spacious areas in elevators and circulations (i.e., slack of physical area) to include new or emergency processes and obese patients. (I, R)	X	X	X	X	X	X	X	X	X	X	X
38. Using partitions with drywall or other flexible technologies that allow further adaptation, if necessary. (O, I)	X	X	X	X	X	X	X	X	X	X	X
39. Designing circulation areas that include manoeuvring space to large equipment. (O, I, R)	X	X	X	X	X	X	X	X	X	X	X
40. Designing alternative routes in case the usual route is closed (e.g., in case of elevator maintenance). (O, I)	X	X	X	X	X	X	X	X	X	X	X
41. Designing multiuse spaces that have a regular use but can serve as a warehouse of equipment and supplies during crises or in times of building transition. (O, I)			X		X	X			X	X	X
42. Providing power plugs in the corridors for equipment recharging during the transportation of critical patients. (O, I)	X	X	X	X							
43. Designing backup areas for expanding ICU bed capacity during crises such as the COVID-19 pandemic. The infrastructure of these areas (e.g., oxygen and electricity supply) should be as close as possible to that of the designed ICUs. Interactions between the backup ICU and other hospital units should also be anticipated in design. (O, I)	X		X			X					
44. If the change of the patient's stretcher is unavoidable, define an area with sufficient size to carry out the change, considering two stretchers side-by-side with the teams around. This can be necessary, for example, when transferring patient from stretcher to bed in the surgical room or radiology. (O)		X	X	X							
45. Designing transition spaces between hallway and industrial kitchen to accommodate lines for employees and equipment (e.g., waiting areas with seating and parking spaces). (O)							X				
Total of practical examples per flow	**7**	**7**	**9**	**7**	**6**	**7**	**6**	**5**	**6**	**6**	**6**

materials. The ICU spreads over two floors, 6th and 7th, of a 7-floor building. There were around 380 employees, involving doctors (64), nurses (60), nurse technicians (190), physiotherapists (5), speech therapists (2), nutritionists (2), nutrition technicians (5), social assistants (2), pharmacists (2), and pharmacy technicians (8), pharmacy professors (3), residents (7), multi-professional residents (14), administrative staff (9), and cleaning staff (10). The average length of patient stay is seven days. Specialized and sophisticated life-supporting devices are necessary such as haemodialysis machines (14), equipment for extracorporeal membrane oxygenation for cardiovascular or pulmonary failure (3), oxygen cylinders (3), intra-aortic balloons (2), and physiotherapeutic objects (400).

The service flows that interact with the ICU were divided into two main groups, related to people and supplies. There were five flows related to people: the resuscitation team, which was physically based in the ICU but provided on-call assistance to all hospital units, patient admission, patient discharge, patient exams, and visitors (including family). As for supplies, there were six flows, involving drugs and medical supplies, sterilized materials, dietary, cleaning, clothing, and waste. The 11 flows span large horizontal and vertical distances, spread over two interconnected buildings (the new one with seven floors and the old building with 13 floors). The flows occurred mostly in the common circulation areas between hospital units (e.g., corridors, elevators, sidewalks, and roads), the warehouse elevator, as well as in the pneumatic tube system (Figs. 2 and 3).

The warehouse elevator is commonly used to transport supplies and medical materials, connecting hospital units (e.g., central pharmacy and warehouse, and sterilized materials centre). In turn, the pneumatic tube system (Fig. 3) is composed of a network of tubes under conditions of vacuum, for the transportation of drugs, blood samples, and other small supplies between hospital units.

Table 4 and Fig. 4 present the characteristics of the service flows, the related c-ICU areas, and the hospital units that interact with the ICU. The cells marked with an X indicate that there is a service flow connecting the hospital unit and the ICU.

The longest flow involves the transportation of clothing, accounting for approximately 290 m (266 m horizontal and 24 m vertical) between the ICU and the clothing unit. By contrast, the flow of supplying the ICU with sterilized materials is the shortest, accounting for about 54 m (50 m horizontal and 4 m vertical). The emergency department (ED) is the unit with the largest number of service flows (three) connected with the ICU, namely those related to the resuscitation team, examination and admission of patients. This makes sense as admission to the ED often precedes ICU admission.

Table 10
Practical examples associated with the BE design prescription "design for the prevention of infections and contamination".

Design for the prevention of infections and contamination											
Flows	People					Supplies					
	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
Practical Examples	**46.** Redefining flows and uses of existing areas to prevent infections and contamination (e.g., dedicated waiting rooms for patients suspected of contamination, dedicated collection and distribution routes for contaminated clothing and waste). (O, I, R)										
	■	■	■	■	■	■	■	■	■	■	■
	47. Creating only a few points of access to restricted areas, in order to reduce unwanted traffic. (O, I, R)										
	■	■	■	■	■	■	■	■	■	■	■
	48. Placing hand sanitizers in the corridors and at the entrance of the hospital units. (O, R)										
	■	■	■	■	■	■	■	■	■	■	■
	49. Designing devices to seal possible contaminated materials that need to be transported. (O, I, R)										
						■				■	■
	50. Designing dedicated routes, at least partly, (e.g., dedicated elevators) between restricted areas, such as for the transit of sterilized materials and the access to the warehouse elevator. (O, I, R)										
								■			
	51. Designing devices to prevent clothes from falling out of the cage during clothing transportation (e.g., rails). (O)										
										■	
	Total of practical examples per flow										
	3	**3**	**3**	**3**	**3**	**4**	**3**	**4**	**3**	**5**	**4**

4.2. Development of the knowledge framework for the design of BE supportive of RP in internal logistics

In this section, seven design prescriptions and 63 examples are presented. In addition to these results, there is a supplementary material composed of photos that visually illustrate the findings. Note that, from Tables 5–11, the shadowed lines indicate the association between examples and flows - e.g., the full shadowed line below example 1 conveys that this example is applicable to all service flows. The total number of examples per service flow is provided at the bottom row of the tables. The sources of the examples are also presented, whereas I stands for interviews, O for observations, and R for regulation. Considering all 63 examples, their origin according to sources was as follows: 44% from both interviews and observations; 25% from all sources; 13% from observations; 8% from both observations and regulations; 5% only from interviews; 3% from both interviews and regulations; and 2% from regulations. As such, 80% of the examples originated from at least two sources of data, reinforcing their credibility.

The design prescription "designing safe, efficient, and flexible routes between hospital units" addresses three complementary performance dimensions and includes nine examples (Table 5). Only example 1 (i.e., creating direct connections between hospital units) is applicable to all flows, while example 2 (i.e., positioning of columns should allow space for manoeuvring) is the second most applicable, being relevant to 10 out of the 11 flows. Thus, both examples 1 and 2 pose either constraints or opportunities for a wide range of logistics activities.

Although other examples (6, 7, 8, 9) are limited to one flow, they have relevant implications. To illustrate, the uptake of example 7, related to avoiding curves in the pneumatic tube, prevents blockages that otherwise could lead the tubes to stop working and delaying the delivery of drugs. These delays can trigger the need for using other drugs as replacement (i.e., a resilient action) and/or delays in the administration of drugs to patients.

The design prescription "assess the pros and cons of centralisation versus decentralisation of support areas that serve several hospital units" encompasses five practical examples (10–14), according to Table 6. The examples most applicable (10 and 11) highlight the benefits of centralized support areas to make the best use of resources such as personal protective equipment and facilities for exams. By contrast, examples 13 and 14 highlight the benefits of decentralisation such as decentralised supporting rooms (e.g., deposits of materials and waste) to reduce movement of staff. In fact, during the meeting to discuss the final results, a nurse highlighted that both centralization and decentralization can co-exist for the same family of materials. She used the case of sterilized materials to make this point, mentioning that some of these materials can be best stored at the ICU nursing stations while others are best stored in a central room at the ICU – it depends on the pattern of demand of each instrument in each ICU.

The design prescription "giving visibility to flow interferences, obstacles, and risks that compromise safety, efficiency, and flexibility" encompasses 14 practical examples (15–28) (Table 7). Two of these examples apply to all service flows: installing mirrors in the corridor crossings to ensure the visualisation of incoming flows is important when transporting patients and over-sized equipment (example 15); and balancing the need to keep restricted access with freeing access during emergencies (example 16).

Another design prescription is "use visual management for the identification of spaces, resources, and processes". It is associated with seven practical examples (29–35) as shown in Table 8. There are two examples applicable to all flows: using signage to increase awareness of changes in flows and spaces during times of crisis (29), and self-explanatory flow directions through the use of colours and symbols (30). The applicability of these examples stems from their benefits to wayfinding, which is a widely known concern in healthcare facilities. The other examples correspond to more specific visual management applications, being useful for the elimination of non-adding value activities such as rework and searching for materials, places, or people.

The design prescription "provide slack resources to cope with disruptions" is related to 10 practical examples (36–45), according to Table 9. Five examples (36–40) apply to all flows. Example 36 refers to having "no break" devices in the elevator to provide at least one hour of autonomy of elevator functioning in cases of power shortage. Example

Table 11
Practical examples associated with the BE design prescription “use technologies supportive of safe, efficient, and flexible service flows”.

Use technologies supportive of safe, efficient, and flexible workflows											
Flows	People					Supplies					
	Resuscitation	Exams	Admission	Discharge	Visitors	Drugs and Medical Materials	Dietary	Sterilized Materials	Cleaning	Clothing	Waste
Practical Examples											
52. Using furniture, finishing and coating materials that facilitate cleaning and disinfection activities – e.g., furniture without roughness, surfaces with as few grooves or crevices as possible, coating materials that do not require the application of wax on the floor. (O, I, R)	■	■	■	■	■	■	■	■	■	■	■
53. Automatic levelling of all lifts with the floors. For patient lifts, the movement of the doors must be delayed with a minimum interruption of 18 seconds. (O, R)	■	■	■	■	■	■	■	■	■	■	■
54. Preventing noise in the corridors using practices such as televisions on mute, with subtitles, and wheels of stretchers and trolleys that allow for smooth transportation flow. (I)	■	■	■	■		■	■	■	■	■	■
55. Putting handles to easily push carts during transportation (e.g., carts of patients’ meals, crashing and clothing cages). (O, I)	■	■				■	■	■	■	■	■
56. Designing device to temporarily hold the fire door open during the team's passage in an emergency such as in a patient resuscitation call. (O, I)	■	■	■	■							
57. Using flexible ICU beds that make it unnecessary to change to another bed/stretcher for transportation between hospital units. Such flexible beds should accommodate the attachment of equipment (e.g., monitors, infusion pumps, and oxygen cylinders) and allow procedures in the surgical centre (e.g., use of saw and perforator, tracheostomy). (O, I)	■	■	■	■							
58. Provide handrails on at least one side wall in corridors where patients circulate - at a height of 80 cm to 92 cm from the floor and with a curved end; crash rails can also be used as handrails. (R)			■	■							
59. Designing pneumatic tube stations that easily adapt to new installations when pneumatic systems are updated. (O, I)		■				■					
60. Call and arrival notices of the resuscitation team should not disturb other patients (e.g., using flashes in the electronic record and visual devices in points seen by teams and not by patients). (O, I)	■										
61. Using cleaning machines that wash and vacuum the floor simultaneously, improving efficiency. (O, I)									■		
62. Implementing alerts (e.g., via cell phone) to indicate when storages of waste are full and need to be collected at the units. (I)											■
63. Providing chute or similar installations that facilitate the collection of dirty clothing from hospital units using the force of gravity. (O, I, R)										■	
Total of practical examples per flow	**7**	**7**	**6**	**6**	**2**	**5**	**4**	**4**	**5**	**5**	**5**

37 concerns spatial slack in common areas in order to accommodate emergencies, possible new processes and/or subsets of patient profiles (e.g., obese). The relevance of this prescription was highlighted by the participants of the meeting in which the final results were discussed. According to the architect, changes in the hospital managerial and care processes occur in a much faster pace than changes in the BE. Thus, the BE is more often than not lagging behind the needs of caregivers, which makes it important to provide slack resources that offer alternative solutions while the BE is not adapted to the new demands.

Table 10 presents six practical examples (46–51), related to the prescription “design for the prevention of infections and contamination”. An idea underlying most examples is the reduction of interactions between flows of people and supplies. Thus, even the examples with fewer corresponding service flows (50 and 51) involve keeping people and supplies away from sources of contamination.

The last design prescription is stated as “use technologies supportive of safe, efficient, and flexible service flows”. The use of these technologies can demand the management of trade-offs – e.g., aural alarms to notify the arrival of the resuscitation team (60) can be noisy and hinder patient comfort. This prescription is based on 12 practical examples (52–63), as shown in Table 11. Examples 52 and 53 account for all flows, being related, respectively, to the use of furniture, finishing and coating materials that facilitate cleaning and disinfection activities, as well as to the installation of devices to ensure that elevators are levelled with the floors.

The technologies accounted for by the examples range widely in

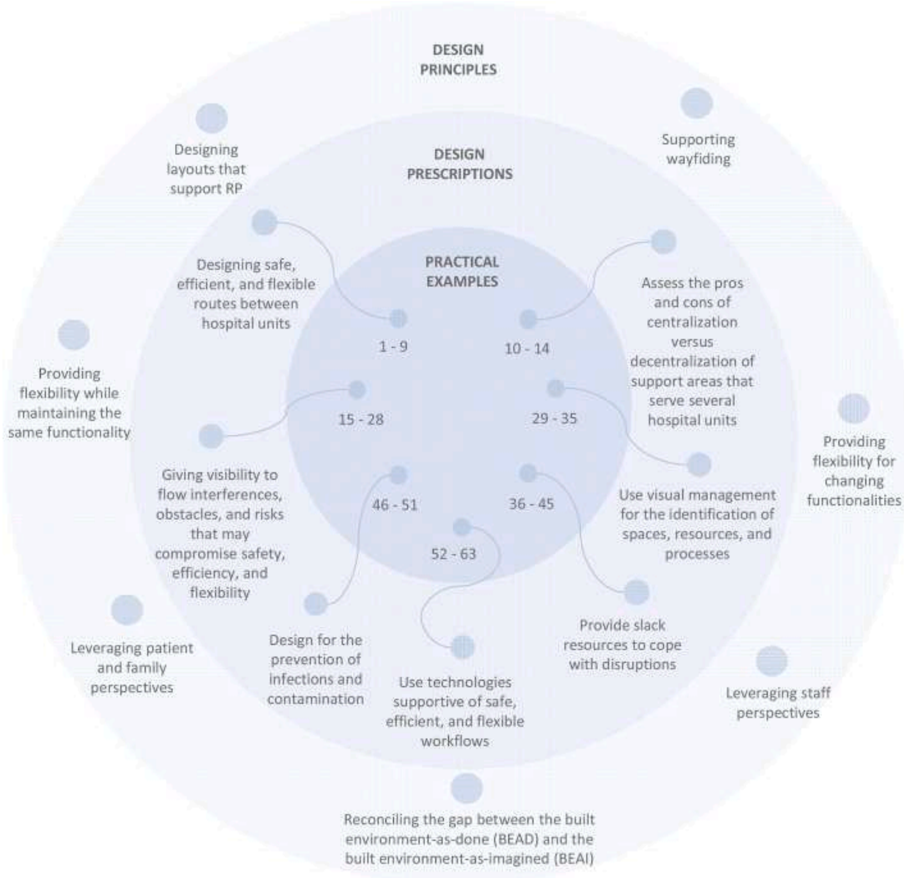

Fig. 5. Schematic representation of the BE design knowledge framework levels and their connections.

terms of cost, from cheap trolleys' handles (55) to expensive flexible ICU beds (57). Thus, technologies are not equally affordable by all healthcare organizations, highlighting the point that RP can be costly. The exemplified technologies have an impact on the safety and well-being of both patients and providers. Patient safety implications are illustrated by example 56, which addresses the need to hold the doors open for teams passing. This is necessary in cases of urgencies such as transporting patients to the ICU or moving the crash cart for patients' resuscitation.

5. Discussion

Fig. 5 schematically presents the BE design knowledge framework that addresses the research question, being composed of design principles, design prescriptions, and practical examples. In common, all principles, prescriptions, and examples, share the purpose of supporting RP. Prescriptions and examples focus on hospital internal logistics, whereas the examples indicate possible concrete design decisions or actions that translate the prescriptions into practice. Thus, the framework accounts for actions or decisions (i.e., prescriptions and examples) to achieve an effect (i.e., RP), consonant with the recommendations of Vaishnavi and Kuechler (2015) for the development of design knowledge.

The design principles are generic and underpin either all or some of the prescriptions (Kuechler and Vaishnavi, 2012) – e.g., the principle of leveraging staff perspective underlies all prescriptions. Indeed, the design principles that served as a starting point for data coding (Ransolin et al., 2022) proved to be sufficiently generic for the identification of examples and prescriptions of logistics relevance such as routes and centralisation versus decentralisation trade-offs. Thus, this study demonstrated the applicability of the design principles to a different context, giving rise to new prescriptions and practical examples. Due to the myriad of relationships between principles and prescriptions, their connections are not depicted through lines in Fig. 5 as this would make the representation too cluttered.

The prescriptions are related to each other and they are context-dependent; this makes sense as RP is also context-dependent (Anderson et al., 2020). For instance, the prescription related to the use of technologies supportive of safe, efficient, and flexible workflows can contribute to the prescription for safe, efficient, and flexible routes. Moreover, the effectiveness of these prescriptions depends on contextual factors (e.g., caregivers qualified to operate the technologies, and structural constraints hindering the renovation of old buildings for the improvement of routes). There can also be conflicts between the prescriptions – e.g., designing for the prevention of infections can create closed spaces that hinder the visibility of service flows. Further, not all prescriptions can be equally affordable by different hospitals. Thus, the framework must be regarded as a source of ideas to designers rather than a template for full compliance. In fact, trade-off choices are commonplace in BE design in general (Jallow et al., 2014).

Moreover, considering that the BE characteristics are long-lasting and relatively static over time, flows constrained by the BE can work under degraded conditions for a long time. This situation offers plenty of opportunities for the rise of resilient practices developed on the spot by workers, not rarely creating new hazards (Ransolin et al., 2020). Some of these implications are implicit in earlier studies of hospital internal logistics that do not frame certain problems as BE issues (Moons et al., 2019; Cubukcuoglu et al., 2021). In fact, prior studies paid scant attention to a number of details revealed by the present work – e.g., dimensions of the corridors that make up the routes and provision of power plugs on hallways. The high level of granularity of this study is intended to resonate with both logistics and architectural designers.

Decisions made by both professional groups are strongly inter-related as they share the ultimate purpose of supporting the RP of health services. These interfaces between design disciplines are frequently ill-addressed in the design process (Soliman-Junior et al., 2022). Workers are forced to fill out gaps in design at the cost of their own safety and health (Terra et al., 2023). This overuse of RP at the front-line can play out, for example, in using long and unsafe routes, as well as in exposure to contamination when sharing elevators with infected patients.

In this respect, it is worth making explicit the relationships between the proposed knowledge framework and the four potentials for RP. The potential of **monitoring** is logically related to the prescription on visual management as it allows people to monitor the service flows through healthcare facilities that should be as intuitive and self-explanatory as possible. In turn, the potential of **anticipating** plays out as a consequence of planning slack resources since these are usually designed to cope with anticipated disturbances.

As for the **responding** potential, it can benefit from slack resources, technologies supportive of service flows, and visibility of flow interferences. The responding assets provided by the BE manifest both in prepared responses that do not need to be activated by people (e.g., designing a device to temporarily hold the fire door open during the team's passage in an emergency) and responses that need human action on the spot – e.g., reacting to incoming traffic by looking at mirrors in the corridors' crossings. Both types of support reinforce the point that the BE poses long-term opportunities and constraints to RP (Ransolin et al., 2020). As for the **learning** potential, it can be more closely and logically related to the BE design prescription on assessing the pros and cons of centralisation and decentralisation. Understanding these pros and cons will improve by learning about past experiences that prioritised either centralisation or decentralisation.

Additionally, the proposed knowledge framework fits the concept of design for resilient performance (DfRP), defined in section 2. Disconzi and Saurin (2022) propose principles of DfRP that expand the four resilience potentials. One of these principles recommends the use of multiple perspectives in design, which is related to the previously mentioned combination of the expertise of logistics and architecture designers. Disconzi and Saurin (2022) also argue that DfRP should allow for acceptable performance even under degraded conditions. This is implicit in several practical examples, whose value to managers may only become clear under degraded conditions of hospital operation. For instance, during the COVID pandemic – arguably a prolonged degraded condition for health services - the frequency of transportation of patients to and from ICUs increased significantly (Pande et al., 2020). This revealed the value of facilities such as power plugs on hallways and designing alternative routes, which in normal times could be seen as unnecessary slack. Finally, the knowledge framework is primarily a contribution to RP at the meso level of hospital services, where meso is the level that permeates and connects the activities of individual hospital units (micro level). Contributions to the macro level might occur if the findings of this study are confronted with the requirements set by building code regulations and standards, which currently do not pay explicit attention to RP (Øyri, 2021).

6. Conclusions

The research question that guided this work concerned the development of BE design knowledge supportive of RP in hospital internal logistics. It was answered by the seven design principles, seven design prescriptions, and 63 practical examples that comprise the knowledge framework shown in Fig. 5. This framework offers a new perspective of resilient internal logistics in hospitals, by making BE implications explicit. This is in contrast to earlier studies, where BE issues were not framed, resulting in missed details and information. Thus, the present study bridges a gap between internal logistics and architecture in the context of healthcare facilities. Relationships between the framework and resilience theory were made explicit by discussing the findings from the viewpoints of the four resilience potentials and the principles of DfRP. This discussion positioned this research as a contribution to understanding RP at the meso level of hospital services.

Some limitations of this study must be mentioned. First, it was based on a single case study, which may restrict the generalizability of the findings, although the case study of a large hospital provided rich information. Second, the implementation of the framework for the design (or re-design) of internal hospital logistics was not addressed. Such implementation is dependent on a number of contextual factors, such as cost, product development process, and local regulations. Also, the effectiveness of using the framework can be influenced by the level of integration with other product development approaches. Third, the interactions between the service flows were not explored in details, which is important as they share the same physical infrastructure.

This work also gave rise to several opportunities for future studies, as follows: (i) to develop similar knowledge frameworks for other service flows such as those related to surgical units; (ii) to identify opportunities for improvement in regulations and standards, based on the knowledge framework; (iii) to investigate the interactions between the service flows; (iv) to assess how the framework is complementary to design guidelines from other areas such as operations management in hospital logistics (e.g., algorithms for the scheduling and sequencing of service flows); (v) to develop an electronic repository of good practices of applying the knowledge framework, contributing to its continuous updating and expansion, besides offering an accessible source of ideas to designers; and (vi) to apply the framework in the design or re-design of hospital internal logistics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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APPENDIX J – Paper as accepted for publication (Paper III)

Beyond the Operating Room: Built Environment Design Knowledge Supportive of Resilient Surgical Services

Abstract

Purpose: surgical services are settings where resilient performance (RP) is necessary to cope with a wide range of variabilities. Although RP can benefit from a supportive built environment (BE), prior studies have focused on the operating room, giving scant attention to support areas. This study takes a broader perspective, aiming at developing BE design knowledge supportive of RP at the surgical service as a whole. **Methodology**: seven BE design prescriptions developed in a previous work in the context of internal logistics of hospitals, and thus addressing interactions between workspaces, were used as a point of departure. The prescriptions were used as a data analysis framework in a case study of the surgical service of a medium-sized private hospital. The scope of the study included surgical and support areas, in addition to workflows involving patients and family members, staff, equipment, sterile instruments and materials, supplies, and waste. Data collection included document analysis, observations, interviews, and meetings with hospital staff. **Findings**: results identified 60 examples of using the prescriptions, 77% of which were related to areas other than the operating rooms. The developed design knowledge is framed as a set of prescriptions, examples, and their association to workflows and areas, indicating where it should be applied. **Originality**: the design knowledge is new in surgical services and offers guidance to both BE and logistics designers.

Keywords: built environment, design, surgical services, resilience.

Article classification: Research paper.

1. Introduction

Surgical services interact with a number of hospital units, such as the sterile unit, in-patient wards, the intensive care unit (ICU), pharmacy, and maintenance (Chraibi *et al*., 2019; Moons *et al*., 2019). There is also diversity as there can be individual preferences of surgeons in terms of work organisation arrangements, team composition, and tools (Clay-Williams and Cartmill, 2023). Due to these interactions and diversity, in surgical services, as with other health services, there tends to be a gap between work-as-done, which reflects what really happens in the workplace, and work-as-imagined, corresponding to what was supposed to occur according to plans, procedures, and policies (Hollnagel, 2014). The fallout of this is, to a degree, circumvented by the resilient performance (RP) of systems of care provision. RP is an emergent systems property expressed as the capacity to monitor, anticipate, respond, and learn from expected and unexpected variabilities (Hollnagel, 2017).

Although socio-technical systems such as surgical services are intrinsically resilient to some extent (otherwise they would cease to exist), work system design plays a crucial role to support RP (Wiig *et al*., 2020; Disconzi and Saurin, 2022). This includes the built environment (BE) design, which shapes the service flows and participants´ wellbeing (Halawa *et al*., 2020; Capolongo *et al*., 2020; Marshall and Touzell, 2020). Earlier studies of BE in surgical services focus on the internal configuration of operating rooms, addressing issues such as clutter caused by cables (Joseph *et al*., 2022; Neyens *et al*., 2019; Taaffe *et al*., 2023), and layouts that hinder patient visibility, communication among team members, and the movement of materials and people (Palmer *et al*., 2013; Taaffe *et al*., 2023; Bayramzadeh *et al*., 2018). Ceiling-mounted booms, workstations-on-wheels, wireless devices, standardisation of the layout design across operating rooms, and accessible light switches and power plugs have been proposed as means to cope with some of those issues (Taaffe *et al*., 2023; Jurewicz *et al*., 2021; Watkins *et al*., 2011; Gurses *et al*., 2012).

While important, these studies neglect the flows between operating rooms and support areas, and the corresponding BE (Gurses *et al*., 2012; Rapport *et al*., 2020). The need for considering these flows is exemplified by the process of setting up operating rooms, as surgical supplies and staff from several spatially dispersed locations need to arrive on-time, and be of the right type and in the correct number, thus demanding synchronisation of several logistics processes (Ahmadi *et al*., 2019; Göras *et al*., 2019; Payne *et al*., 2012). Therefore, BE design of surgical services must be based on inputs from a wide variety of professionals, not only from those who spend most of their time inside operating rooms (Patkin, 2003; Bayramzadeh *et al*., 2018). Hence, this study hereafter defines surgical services as the broad setting of operating rooms and direct support areas that contribute to the functioning of this hospital unit. This perspective expands the scope of prior studies limited to operating rooms, and also requires the investigation of how operating rooms interact with support areas, encompassing the corresponding workflows that are shaped by the BE. It is also consonant with the emergent character of RP, which arises from interactions between multiple social and technical elements (Wachs *et al*., 2016). Earlier studies of BE in surgical services do not explicitly address resilience implications, and they are overly focused on operating rooms.

Against this background, the research question addressed by this paper is framed as follows: how can we develop built environment design knowledge that supports resilient performance in the internal logistics of surgical services? The expression design knowledge refers to both prescriptions and practical examples of their application in surgical services, along with the workflows and BE areas where it should be applied. Prescriptions are suggestions for action in a given circumstance to achieve an effect (Vaishnavi and Kuechler, 2015). Seven BE design prescriptions supportive of RP in the context of hospital internal logistics to and from ICUs, devised by Ransolin *et al*. (2024), are used as a basis for developing design knowledge tailored to the context of surgical services. This choice stems from the expanded view of surgical services adopted in this paper, which gives prominence to logistics activities (e.g., movement of people and materials) to and from operating rooms. The types of logistics service flows impacted by the BE in Ransolin *et al.* (2024) are the same approached in this study, albeit in a different context. The research question was investigated in a case study of one surgical service in a private, medium-sized teaching hospital in Australia.

2. Background

2.1. Surgical service flows

Surgical services involve activities associated with eight main service flows (Machry *et al*. (2021): patient, family, surgical team, anaesthesiology team, movable equipment, supplies, sterile instruments and materials, and waste. The patient flow is the most important one, interacting multiple times with the other flows (Fredendall *et al*., 2009). Surgical services involve three perioperative phases from patient admission to discharge (AusHFG, 2018): (1) preoperative, including patient preparation prior to the transfer to the operating room; (2) intraoperative, in which the intervention takes place; and (3) postoperative, which begins with the post anaesthesia recovery, followed by the second and third recovery stages, when the patient is ready to be transferred to a hospital inpatient unit or discharged (AusHFG, 2018).

Nurses are usually involved in the perioperative phases as they perform or support many of the service flows (Machry *et al*., 2021). Technologies also play a key role. For instance, equipment should be easy to move inside the operating room, such as the workstation-on-wheels, and the examination machinery shared among operating rooms. Surgical instruments are a key supply and they are organised into trays in carts to facilitate operating room setups and must be sterilised after every use. Supplies also include medical consumables (e.g., surgical drapes, gloves, syringes), and medical materials often held in consignment with the supplier up to its consumption after the surgeries (e.g., orthopaedic instruments). Additional supplies include items such as drugs, linen, and food (Moons *et al*., 2019). Waste flows include general waste, used consumables and their packages, and bio-medical waste, all referred to as dirty flows that should not intersect with patients or clean sterile and non-used items (Payne *et al*., 2012).

2.2. Prescriptions for the design of built environment supportive of RP

The BE design can either facilitate or hinder RP, such as by shaping the flows of patients, staff, visitors, equipment, and information (Pati *et al*., 2008). These implications are long-lasting as the BE, at a macro-scale, is relatively static over time. However, workers commonly adapt to the constraints posed by the BE, such adaptations playing out in changes at a micro-scale such as in the positioning of furniture and work organisation (Ransolin *et al*., 2020).

Ransolin *et al*. (2022) carried out a systematic literature review on the influence of the BE on RP. The authors developed a generic structure of BE design knowledge supportive of RP in health services in general, without focusing on specific units or process. These findings were used by Ransolin *et al*. (2024) as a basis for the development of new prescriptions and examples related to the common hospital areas (e.g., elevators, corridors, sidewalks) linking ICUs to other hospital units. Several workflows take place in these areas. The corresponding case study occurred in a large teaching hospital in Brazil, giving rise to seven new design prescriptions supportive of BE in the internal logistics of hospitals (Table I).

Design prescriptions (Ransolin *et al*. 2023)		**Resilience rationale**
1	Design safe, efficient, and flexible routes between hospital units	Resilient systems benefit from safety (otherwise they will be disrupted by accidents), efficiency (which prevents unnecessary complexity stemming from wastes and releases resources for performance adjustment), and flexibility (which provides alternative courses of action) (Hollnagel 2009).
2	Assess the pros and cons of centralization and decentralization of support areas that serve several hospital units	RP includes the management of trade-offs as in the face of scarce resources is rarely possible to excel in multiple performance dimensions (Woods 2015, Hollnagel 2009).
3	Give visibility to flow interferences, obstacles, and risks that may compromise safety, efficiency, and flexibility	Making variations in performance visible, preferably in real-time, supports RP (Disconzi and Saurin 2022) as it is about coping with both expected and unexpected conditions.
4	Use visual management for the identification of spaces, resources, and processes	The functioning of complex socio-technical systems should be intuitive for their users, supporting quick and accurate decision-making in face of variabilities (Clegg 2000, Galsworth 2017).
5	Provide slack resources to cope with disruptions	Slack resources are defined by Bourgeois (1981) as a cushion of actual or potential resources which allows an organization to adapt successfully to internal pressures for adjustment or to external pressures for change in policy. Slack resources can take many forms such as financial reserves, extra space, surplus of materials, workers on standby, redundant equipment, and generous time margins, among others (Saurin and Werle 2017). Such resources make processes loosely-coupled, absorbing variabilities and buying time for RP.
6	Design for the prevention of infections and contamination	All hospital users must be safe against existent and new epidemiological hazards arising from the local context. This is a dimension of safety, which is important for RP as mentioned in the aforementioned rationale for prescription 1.
7	Use technologies supportive of safe, efficient, and flexible workflows	Technologies amplify physical and cognitive human capabilities, therefore expanding opportunities for RP, although they may create new drawbacks if their design does not account for work-as-done (Barrett 2022).

Table I - Prescriptions for the design of BE supportive of RP in the internal logistics of hospitals and their resilience rationale (based on Ransolin et al. 2024).

Although these prescriptions were not originally conceived for surgical services, extant literature suggests that they are applicable to that context. Firstly, the prescription of designing safe, efficient, and flexible routes between hospital units also applies to routes within surgical services. For instance, patient handovers between perioperative phases benefit from short and unobstructed routes (Rapport et al., 2020; Abraham et al., 2023). Regarding the second prescription, the issue of trade-offs between centralised and decentralised support areas also applies to such areas located within surgical services – e.g., nursing stations and storage rooms may (or not) be centralised serving all operating rooms (Reiling et al., 2008; Ahmadi et al., 2019). The third prescription, related to the visibility of flow interferences, obstacles, and risks, is applicable, for instance, by defining visual boundaries between non-sterile and sterile areas within a surgical service (Rapport et al., 2020). The fourth prescription, concerned with visual management for the identification of spaces, resources and processes, is relevant, for example, for the indication of the need for wearing gowns before entering the intraoperative area (Chraibi et al., 2019). The fifth prescription can be illustrated by the need for an operating room reserved for urgent, unscheduled surgeries (Ahmadi et al., 2019). The sixth prescription, related to the prevention of infections and contamination, is crucial as patients are particularly vulnerable to contamination during a surgery, and part of these risks can be reduced by limiting the transit of people and materials to and from the operating room (Neyens et al., 2019; Halawa et al., 2020; Ahmadi et al., 2019). The seventh prescription, which addresses technologies supportive of workflows, can be illustrated by the use of equipment of size and shape that do not hinder patient visibility and access by the clinicians (Pati et al., 2008; Moore et al., 2010). Despite the applicability of the prescriptions, this does not mean that they suffice to surgical services. There is a need for a systematic approach for translating them to the surgical context, offering implementation examples and identifying the affected workflows.

3. Research Method

3.1. Research design

The case study research strategy was chosen, as it enables exploration of social-technical phenomena in real-world settings (Flyvbjerg, 2011). This is aligned with the research question concerned with BE supportive of RP, which is a topic of socio-technical nature. Further, the development of BE design knowledge requires an understanding of the functioning of surgical services, which are complex settings that benefit from the holistic case study approach.

The case study was conducted in a hospital that carries out a broad range of surgical procedures, encompassing a wide diversity of surgical service flows, offering a suitable context for this study. The setting was a medium-sized private teaching hospital servicing a high socio-economic population in a metropolitan area of New South Wales (NSW), Australia. The complex consists of a 5-floor building that opened in 2010 with around 22,000 square meters. It comprises 144 beds, four inpatient wards, 13 operating rooms within the surgical service, two cardiac and angiogram suites, two endoscopy rooms and 20 ICU beds, and the provision of oncology, chemotherapy, radiotherapy, imaging, and pharmacy services. The surgical service is located on the first floor of the hospital. This unit facilitates the perioperative phases of surgery, mostly for patients scheduled under elective interventions. A detailed description of the surgical service, including flows and BE, is presented in section 4.2.

Established best practices of case-based research were adopted, including: development of data collection protocols (Eisenhardt and Graebner, 2007); triangulation of data and data sources (Noor, 2008); development of a database, allowing traceability and reinterpretation of data when necessary (Flyvbjerg, 2011); and the use of visual representations to illustrate the contributions of the study (Eisenhardt and Graebner, 2007). This case study had two major stages:

(i) Characterisation of the surgical service and their BE. This started with the selection of surgical service flows, in consultation with an experienced gastroenterological surgeon who has been engaged by the design facility since before the current building construction in 2007. The characterisation of the service was based on the four sub-systems of socio-technical systems defined by Hendrick and Kleiner (2001), namely social, technical, work organisation, and external environment. The BE was characterised by the description of the floor plans and analyses of perioperative phases, areas, and surgical service flows; and

(ii) Analysis of the surgical service in light of the prescriptions presented in Section 2.2. Such analysis made it possible to adapt the prescriptions to the reality of surgical services, also giving rise to several ways, referred to as practical examples, of translating the prescriptions into practice. It also shed light on the interactions between BE, workflows, and RP, highlighting the importance of considering the surgical service as a whole, rather than overemphasising the internal configuration of the operating rooms.

3.2. Data collection

Data collection was conducted by the first author after the study protocol was approved by the Human Research Ethics Committee of the educational institution (Reference number: 520221248843909). Data were obtained directly from the users of the spaces, including administrative, supporting, and clinical staff members. Secondary data were also collected from documentary regulations for the construction of healthcare facilities in NSW and analyses of floor plans. The total hours of data collection and their distribution according to the sources of evidence are indicated in Table II. Firstly, meetings with hospital staff helped to identify interviewees, and define flows and areas from which data would be collected. Then, a first round of observations was conducted before interviews and additional observations were scheduled with staff members. Data collection was discontinued when saturation reached, meaning that findings became repetitive, and the researcher regarded the data collected up to that point as sufficient to address the research goal (Ritchie *et al*., 2003).

Data collection	**Sources of evidence**			
	Document analysis	**Non-participant observations**	**Semi-structured interviews**	**Meetings with hospital staff**
Hours	**-**	**30**	**16**	**6**
Total (hours)	**52**			

Table II – Data collection hours distribution according to the sources of evidence.

Source: Authors own work.

Documentary regulations analysis involved reading guidelines and regulations for planning, designing, and constructing healthcare facilities in NSW, particularly in: Building Code of Australia; the Australasian Health Facility Guidelines, which are followed by health planning units and standard components; the Guide of Wayfinding for Healthcare Facilities, the Health Facility Planning Process guideline, and the Health and the Arts Framework, from the NSW Health; the guidelines regarding managing, planning and design of the perioperative environments, including Postanaesthesia Care Unit (PACU), from the Australian College of Perioperative Nurses; and the Summary of the Australian Guidelines for the Prevention and Control of Infection in Healthcare, from the National Health and Medical Research Council. In these documents, we looked for regulatory requirements that implicitly applied the design prescriptions to the internal logistics of the surgical services, including activities that occurred inside and outside of the operating rooms. The regulations and guidelines documents comprise 1240 pages. The architectural floor plans of the hospital were also obtained and used for linking surgical service flows with the BE features.

Thirty (30) hours of **non-participant observations** were conducted across 14 visits to the setting. In this observation type, the researcher watches the subjects of their study, with their knowledge and experience, without taking an active part in the situation under observation (Scott and Marshall, 2009). Staff members were observed during daily work (e.g., obtaining supplies to setup the operating rooms, and transportation of patients) in the different perioperative phases and their interaction with the BE across service areas. Due to the prescriptions emphasis on activities related to logistics, the observations paid special attention to the interactions of the workflows with the BE – e.g., observations of the setup of the operating room offered insight into several flows of people and materials that spanned most areas of the surgical service. Observations also included flows related to surgeries using different technologies (e.g., robotic), which had different BE implications. During these visits, data were collected via field notes, recordings, and photos.

Sixteen (16) hours of **semi-structured interviews** were conducted with 18 hospital staff members from administrative, supporting, and clinical roles (Table III). Due to the focus of the study on the surgical service, 10 participants were purposively selected from that unit for interview. Moreover, there were eight interviewees from other hospital units that played a supportive role in the daily functioning of the surgical service, such as logistics activities and patient transportation inter hospital units. Following consent by participants, interviews were audio-recorded. Demographic information such as profession, years of experience, and position at the hospital was collected. The interviews were structured around three guiding open questions: could you give an overview of your daily work? How does the BE facilitate or hinder your everyday work? Please illustrate these implications with a situation experienced by you or a colleague. Interviews were carried out in-person and lasted from 30 to 95 minutes (53 minutes on average), totalling 16 hours of recordings.

Interviewees		**Duration of the interviews (min)**
Type	**Number of interviewees and hospital position**	
Administrative staff	1 nurse unit manager	30
	1 ward nurse unit manager*	30
	1 strategic manager	30
	1 theatre floor manager	45
	1 prosthesis coordinator*	45
	1 supply chain manager*	70
	1 associate director of hospital operations*	60
Supporting staff	1 sterile unit manager*	60
	1 supply chain operator (store person)*	60
	1 design team leader - company representative	60
	1 coordinator of patient transportation*	45
	1 environmental services manager*	30
	1 surgeon	60
	1 assistant surgeon	40

Clinical staff	1 anaesthetist	95
	1 nurse (intraoperative: scout/scrub)	50
	1 registered nurse (intraoperative: scout/scrub)	70
	1 nurse (pre and postoperative services)	75
Total	**18 interviewees**	**955 min - 16 hours**

Table III – Interviewees, hospital positions, and duration of the interviews. Notes: * refers to professionals from hospital units other than the surgical service.

Source: Authors own work.

3.3. Data analysis

Data were subjected to a thematic analysis following the steps recommended by Pope *et al*. (2000): familiarisation, identifying themes, coding, charting, and mapping and interpretation. Familiarisation was concerned with the multiple readings of primary and secondary data - i.e., transcripts of interviews and regulations. Field notes and transcripts of interviews accounted for approximately 12,000 words. The themes for analysis were the design prescriptions in section 2.2. Coding involved a deductive process of identification of excerpts of text from empirical data and regulations associated with design prescriptions. This stage gave rise to practical examples that were schematically represented in Tables according to the prescriptions in the charting stage. Thus, such practical examples were not raw data corresponding to implementation in a real and specific scenario. There was a coding effort, even though the resulting codes were relatively less abstract than the prescriptions. Finally, results were discussed in light of extant literature at the mapping and interpretation stage. A schematic representation of how the design knowledge applies to a generic surgical service was also devised based on the findings (see section 5).

4. Results

4.1. Characteristics of the surgical service and their BE

In this section, the surgical service is described according to the four socio-technical sub-systems. The **social sub-system** comprises staff members, patients, and visitors such as family members. Over 300 professionals work in the surgical service, either on a full-time or casual scheme, with an average of 6 years of experience in the setting. Staff members are divided into the following categories: administrative (nurse unit managers, strategic manager, theatre floor manager, and receptionists); supporting (store persons, surgical sales representatives, pathology courier, orderlies, and cleaners); and clinical (surgeons, medical students and residents, anaesthetist, nurses).

Regarding the **technical sub-system**, the surgical service is composed of 13 operating rooms located on the first level of a 5-floor hospital building, occupying approximately 3,170 m². The technical sub-system also encompasses devices, instruments, materials, and supplies. Imaging devices are shared between the operating rooms when necessary, e.g., X-rays, ultrasound, and scopes. Fixed equipment includes robots and Heart-Lung machines for cardiovascular procedures. Operating rooms have ceiling-mounted booms with flexible arms to connect with screens, surgical lights, and power plugs. Sterile instruments and materials are set up a day before the operation, being organised in surgical case carts next to the corresponding operating room. These items can be single-use instruments and implantables – e.g., joint replacements and intestinal staplers; reusable instruments – e.g., forceps, scissors, and retractors; and materials – e.g., drapes, gloves, syringes, and orthopaedic instruments. Supplies encompass non-sterile materials and instruments, drugs such as pain reliefs and anaesthetics, linen, food, cleaning products, hand sanitisers, and soaps.

As for the **work organisation sub-system**, the main service flows are those of patients and family members, staff, equipment, sterile instruments and materials, supplies, and waste. Most surgeries are for day surgery patients, namely outpatients who are admitted and discharged on the same day for procedures of specialties ranging from general, gastroenterology, gynaecologic, ophthalmic, cardiovascular, spinal, neuro, sports medicine, and orthopaedics. The surgical service is open from 7 am to 6 pm on weekdays, and includes a stand-by team on call for emergency surgeries. After 6 pm, staff perform activities such as maintenance, cleaning, and organisation of surgical case carts for the next-day surgeries. The **external environment sub-system** comprises hospital units that interact with the surgical service, such as sterile unit, pathology providers, warehouse, emergency department, central kitchen, pharmacy, environmental services, wards, and ICU. Although most surgeries are elective and scheduled well in advance, there are emergency surgeries involving patients from the ICU and the emergency department.

4.2. Surgical services areas and flows

Figure 1 presents the floor plan of the surgical service. From the total floor area (3,167 m²), 39% (1,238 m²) corresponds to the perioperative areas, while 61 % (1,929 m²) is occupied by the support areas. At the bottom, Figure 1 illustrates the spaces in more detail, distributed according to different levels of access restriction and the representation of service flows.

The patient flow starts in first stage of the preoperative phase, in a waiting area for admission with 27 seats. After admission, the patient is referred to the second preoperative phase, in which there are 14 patient bays, also known as holding bays, where the patient is prepared for surgery. In this phase, the nursing staff checks the patient against allergies and health conditions, the consent form is signed, and the anaesthetist and the surgeon interact with the patient. The patient bay accommodates a bed, wheelchair, space to change into a theatre gown, and chairs for family members. When authorized by the surgical team, the patient is transferred to the third stage of the preoperative phase, corresponding to one of the 11 induction rooms, also known as anaesthetic bays. In this room, the patient is prepared for anaesthesia (e.g., insertion of the cannula and sometimes drugs for pain or anxiety relief) while the operating room is being cleaned from the previous surgery. Patients are anaesthetised only when inside the operating room.

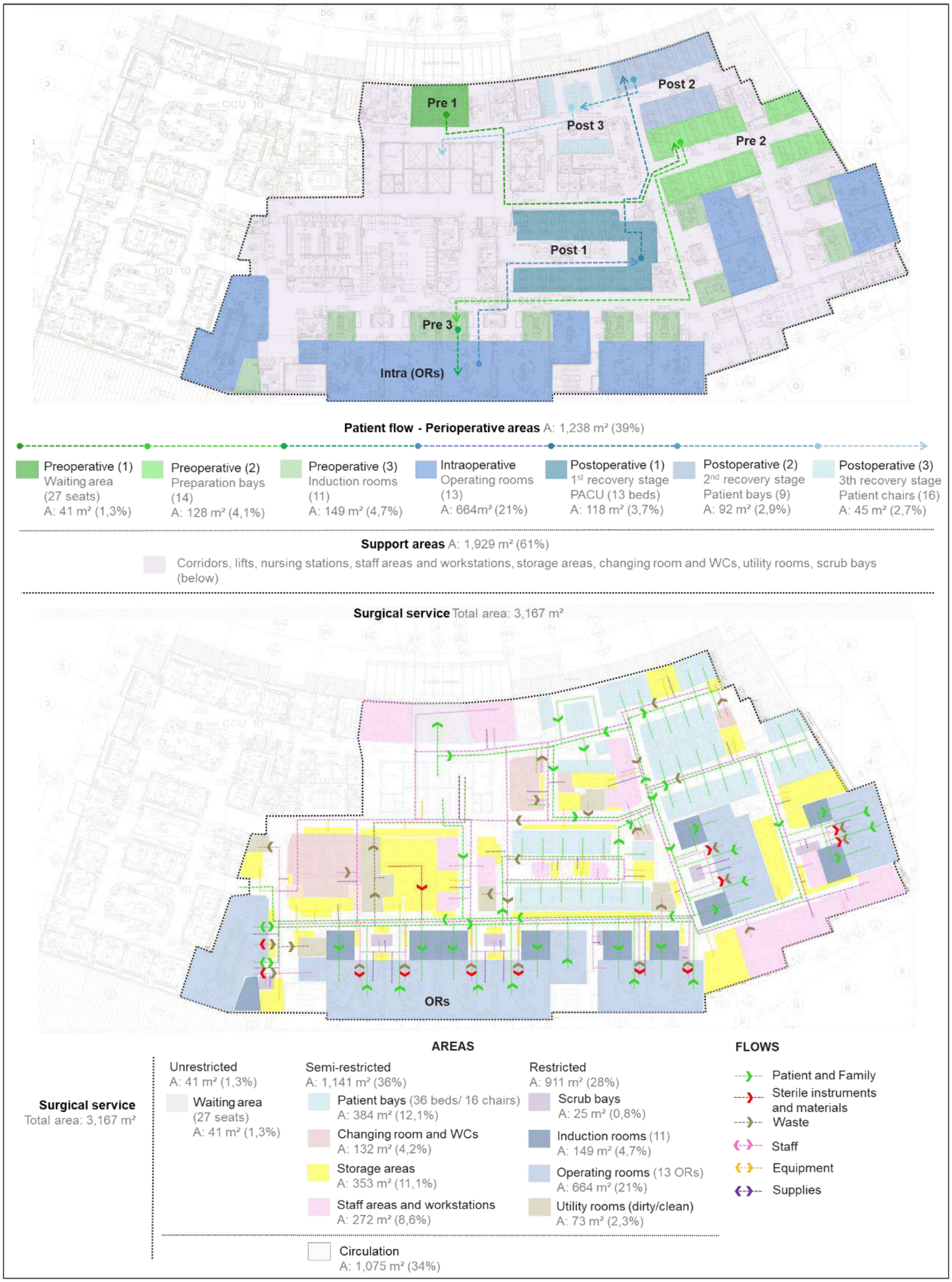

Figure 1 – On the top: perioperative and support areas, the arrows representing patient flow. At the bottom: diagrams of areas, access restrictions, and flows.

Source: Authors own work.

Once the operating room is ready for surgery, the patient flow advances to the intraoperative phase. When the surgical procedure is completed, the patient is transferred to the Postanaesthesia Care Unit (PACU), marking the start of the postoperative phase. In this unit, nurses observe and monitor the patient, which is made easier by a layout with 13 open-plan bays. In some cases, a patient will be taken to the ICU as a planned post-operative admission or because of some unexpected event during surgery. The ICU is on the same floor as the PACU and operating rooms. PACU patients receive surgeon visits, in which the discharge for the following phases is authorised. The patient must be awake before moving to the next recovery stage in a space that has nine open-plan bays. After being ready to move to the next step, the patient goes to the final recovery stage, in a discharge lounge where there are 16 chairs with small tables for quick meals for day surgery patients.

The surgical service´s floor is divided into three zones, namely: unrestricted access, semi-restricted access, and restricted access (AusHFG, 2018). Unrestricted zones (e.g., reception desk) accommodate staff, visitors, and patients. Authorized people can access semi-restricted zones (e.g., holding bays), usually wearing perioperative attire. Restricted zones (e.g., operating rooms) are only accessed by authorised people who must wear perioperative attire. Service flows can be unidirectional or bidirectional. Flows of sterile instruments, materials, and waste are unidirectional to avoid contamination. Sterile items are transported directly from the sterile unit, using dedicated lifts. The flows of supplies, equipment, and staff are bidirectional, as they travel along all spaces to support care delivery during the perioperative and supporting phases.

Contamination risks also exist in the flow of waste, which are contained to be transported to the waste room. After each surgery, the operating rooms receive a general cleaning by nurses and orderlies, focusing on the sterile field around the patient, mopping the floors, and removing the garbage. Reusable items are transported to the clean utility room for an additional cleaning and then sent to the waste room in which dedicated lifts move them to the sterile unit for reprocessing. Furthermore, cleaners undertake a terminal cleaning everyday after the last surgery. The emergency room takes priority over the others for cleaning. Like the terminal cleaning, every long-lasting support activity is performed at night to avoid disruptions. For instance, during the night, the nurses organise and arrange the equipment for the following day´s operations on clearly labelled case carts corresponding to the next day's surgeries. Most surgical specialties are allocated to the same operating room to facilitate the setup, which also considers surgeons preferences.

Supplies such as linen and food are provided by hospital housekeepers daily. Scrub jackets, shirts, and pants are restocked in the changing rooms, according to the capacity of the shelves; sheets and blankets are provided to storage areas to be shared between pre and postoperative areas. Food is delivered to the kitchen of the staff room and nursing stations for patients in the postoperative phase.

4.3. BE design knowledge supportive of RP in surgical services

This section presents 60 practical examples of applying the prescriptions to surgical services (see Tables IV to X). In addition, there is a supplementary material composed of photos that visually illustrate the findings. Some of the prescriptions were reworded to clarify their focus on a specific hospital unit, namely surgical services. The examples are ordered according to their frequency of association with the areas and service flows. This association is highlighted through shadowed lines below each example; associations with areas are represented in pink, and with flows in blue. The total count of examples per areas and flows is shown at the bottom of each table. The sources of the examples are denoted within parentheses, with 'I' signifying interviews, 'O' observations, and 'R' regulatory sources. The distribution of the examples according to their sources was: all sources (45%), from both interviews and regulations (22%), both interviews and observations (15%), exclusively from regulations (10%), from both observations and regulations (7%), and solely interviews (1%). This variety reinforces the importance of using multiple sources of data.

The prescription "design safe, efficient, and flexible routes between perioperative phases" (Table IV) encompasses six examples. Example IV.1 is applicable to most areas and flows, conveying that the BE design can mitigate conflicts between flows. As mentioned by one nurse interviewed, staff do not realise that patients should not be exposed to certain flows: "*we are so desensitized from all of this that people tend to forget that patients shouldn't be seeing what we're showing them - such as dirty bins"* (nurse unit manager). In turn, example IV.6, although less applicable, is nonetheless relevant for prioritising patient care and well-being in patient transfer among perioperative phases.

Design safe, efficient, and flexible routes between perioperative phases										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**IV.1** Ensure the separation between patient and supporting flows, which can be studied based on mock-ups. This can bring benefits such as preventing patients from seeing dirty bins and trolleys where they are crossing. (I, R)									
	■		■	■	■	■	■	■	■	■
	IV.2 Comply with corridor width requirement for clinical areas. Corridors should be wider enough to fit ICU beds that are larger than regular ward beds. Strategies for coping with narrow corridors can include passing bays, accommodating equipment in in-built niches, and prioritization of corridors for certain flows. (I, R)									
				■	■		■	■		
	IV.3 Dimensions of doorways should fit large equipment, such as bariatric patient stretchers, to avoid damaging or patient handling to a smaller stretcher. (I, R)									
	■	■	■	■	■		■			
	IV.4 Pre and postoperative areas should have separate accesses. Patients, sterile instruments and materials, and waste flows should be unidirectional, avoiding return to sterile and restricted areas. E.g., an intubated patient cannot share the corridor with a patient fully awake as it can create anxiety. Thus, patient flow can be a 'circuit' design to enable optimization between these areas. (O, I , R)									
	■		■	■	■				■	■
	IV.5 Ensure a smooth transition (e.g., no bumps or irregularities) between different floor finishes. (R)									
	■		■	■	■				■	
	IV.6 Ease of transfer and access among perioperative phases, using back-of-house corridors. PACU and ICU should be close to operating rooms in order ensure quick patient transfer. (O, I, R)									
				■	■					
	Total of practical examples per areas/flows									
	4	**1**	**4**	**6**	**6**	**1**	**3**	**2**	**3**	**2**

Table IV – Practical examples associated with the design prescription "design safe, efficient, and flexible routes between perioperative phases".

Source: Authors own work.

Table V presents twelve examples (V.1 – V.12) associated with the prescription "assess the pros and cons of centralisation and the decentralisation of resources". The most applicable example (V.1) involves the trade-offs between centralisation and decentralisation of storage areas. Centralized storage is advocated for drugs and general items shared among perioperative phases, while decentralization is recommended for items specific to surgery specialty. Grouping operating rooms based on surgical specialties also facilitates resource-sharing among them. Resource-sharing can also be enabled by clustering similar-purpose areas such as surgical and critical care units (V.3 - V.6). The least applicable example (V.12) is the need for decentralised staff amenities such as toilets and spaces for storing personal belongings. This reduces walking distances.

Assess the pros and cons of centralization and the decentralization of resources										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**V.1** There can be a centralised storage for general items shared among perioperative phases and decentralised storage areas for specific surgical items. Drugs with a higher risk of misuse must be stored in a locked cabinet shared among the operating rooms, allowing control and ready access nurses. In this case, clustering operating rooms according to surgical specialties facilitates sharing resources and ready access to decentralised storage areas. Some operating rooms can have doors linked to storage rooms. (I , R)									
	V.2 Consider the pros and cons of single corridor versus a racetrack model. The first involves sharing the same corridor by all flows and phases. The width should fit the storage of case carts, equipment, and the passageway of at least two flows in different directions. In the second solution, dirty and clean flows are separated through dedicated corridors, preventing patients from crossing equipment, waste, and contaminated instruments. (O, I ,R)									
	V.3 Functional links are necessary between the surgical services and the ICU, interventional angiography, sterile unit, pathology unit, blood bank, imaging centre, and hospital wards. Thus, hospital units with similar procedures can have a central storage of resources to avoid duplication. For example, operating rooms performing angiography and neuro surgeries should be close to the ICU, as cardiac arrest cart and drugs can be shared. (I, R)									
	V.4 Cluster pre and postoperative bays to promote shared use of the spaces as admissions decrease along the day – e.g., the same bays and chairs can be used by patients and family members in both phases. Support areas of these phases such as storage, utility rooms, and toilets can also be shared. (O, I, R).									
	V.5 Place shared resources in the boundary area between the spaces sharing the same resources, with doors for both sides – e.g., a drug storage area between the perioperative phases, allowing access from pharmacy workers without the need to scrub. Similarly, if specimens and blood samples are stored in a semi-restricted area, the pathology courier does not need to scrub when collecting them. (O, I)									

	V.6 Design mirror-reverse operating room layout allows the sharing of resources such as supplies, staff, and circulation spaces. However, a single-handling layout might be more intuitive for staff as all operating rooms have the same orientation (I, R)									
	V.7 If close to each other, some services can share preoperative spaces – e.g., interventional angiography, and imaging centre. Access from adjacent units should be intuitive – e.g., surgical team should know the mechanism to open ICU doors when transporting the patient from operating room. An emergency operating room can have internal doors to the ICU to shorten patient flow. (O, I, R)									
	V.8 Pre and postoperative areas should be designed as open plans to facilitate patient observation from a central nursing station, with shared workstation-on-wheels in between bays. Consideration should be given to meals and refreshments served only for postoperative patients, thus requiring an isolated area to avoid odour spread to fasting preoperative or PACU patients. (O, I)									
	V.9 The method chosen for surgical items delivery affects the design of storage rooms – e.g., if 'just-in-time' deliveries require less storage space, despite a higher frequency of flow of store persons to fill the shelves. A solution to store more items is the mobile racking that creates space for circulation by moving a wheel. (O, R)									
	V.10 The induction room should be close to the operating room to allow the anaesthesia preparation of the following patient. The number of preoperative bays can be reduced when induction rooms are provided. (O, I R)									
	V.11 If centralised, scrub bays can be shared between up to two operating rooms. Similarly, induction rooms can be shared and coordinated with operating room scheduling. Imaging devices and anaesthetic machines can also be shared across the operating rooms or set in the operating room for the same type of surgeries, avoiding rework and duplication of resources. (O, I)									
	V.12 Provide toilets near the staff room/kitchen area, reducing walking distances to the changing rooms. Spaces to store staff belongings, such as dry snacks, could also be provided. (O, I , R)									
	Total of practical examples per areas/flows									
	6	**3**	**5**	**10**	**7**	**7**	**5**	**7**	**4**	**2**

Table V – Practical examples associated with the design prescription "assess the pros and cons of centralisation and the decentralisation of resources".

Source: Authors own work.

The prescription "give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility" (Table VI) is comprised of seven examples (VI.1 – VI.7). Example VI.1 applies to all flows due to its relevance for security and traffic management. Visual demarcation on the floors and signage are suggested to separate dirty item from clean item flows (VI.2). This prescription also emphasizes safe and uncluttered spaces by removing obstacles such as cable cluttering and improper equipment storage (VI.3 – VI.5). Patient safety and well-being are also highlighted, benefiting from central workstations for ease of patient monitoring, and colour schemes (VI.6, VI.7). The least applicable example (VI.7) is related to prioritizing patient flows in support areas and optimizing staff schedules to prevent congestion.

<table>
<tr><th colspan="11">Give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility</th></tr>
<tr><th colspan="5">Areas</th><th colspan="6">Flows</th></tr>
<tr><th></th><th>Preoperative</th><th>Intraoperative</th><th>Postoperative</th><th>Support</th><th>Patient/ family</th><th>Staff</th><th>Equipment</th><th>Supplies</th><th>Sterile instruments and materials</th><th>Waste</th></tr>
<tr><td rowspan="16">Practical examples</td><td colspan="10">VI.1 Reduce and monitor the entrances and exits to the surgical services. Unauthorised access creates operational and security risks such as contamination of sterile areas or theft of drugs. Clear views of these points allow surveillance from the reception desk. Demarcating ‘rings of security’ helps to monitor traffic, which can be aligned with the established area restrictions. (O, R)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10">VI.2 Prevent interactions between dirty and clean flows. Visual demarcation can be useful for that purpose such as lines or colours on the floor and walls to indicate uses such as equipment storage. (O, I, R)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10">VI.3 Avoid clutter as it can create obstacles and risks of slips, trips, and falls. Providing power plugs evenly distributed to reduce the use of extension leads and cables on the floor. Cableless and ceiling-mounted equipment help to prevent slips and falls. In PACU, emergency equipment must be organised and within a reachable distance – e.g., suction, oxygen, emergency basket above with airway adjuncts, and hand sanitiser. (O, I, R)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10">VI.4 Storage spaces should keep doors open to avoid parking the trolley at the doorway to hold. Storage rooms should ideally fit two people simultaneously – e.g., a store person filling the shelves and a nurse picking up an urgent item – with the trolley inside. (O, I, R)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10">VI.5 Avoid place heavy items on top shelves, as they are more likely to fall. Instead, a medium-height shelf with enough stability should be used for those items, as bottom shelves can also cause injury when bending. (O, I)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10">VI.6 The anaesthetist workstation and surgeon should be positioned near the operating table for a visual connection with the patient. Patient physical and visual access during surgery can be provided by movable steps and an operating table with detachable pieces - e.g., arms and legs. Consideration should be given to the colour of TV screens, as it can change organs' colours, and for wall painting that may alter the observer's perception of patient skin tones. (O, I, R)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10">VI.7 Patient flows must always be prioritised in corridors and lifts. Signage for dedicated use is needed during busy surgery days for staff/patient transportation. Levelling the use of staff and changing rooms to avoid peak times is a strategy for smooth flows. (O, I)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10">Total of practical examples per areas/flows</td></tr>
<tr><td>2</td><td>3</td><td>3</td><td>6</td><td>4</td><td>6</td><td>4</td><td>4</td><td>4</td><td>2</td></tr>
</table>

Table VI – Practical examples associated with the design prescription “give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility”.

Source: Authors own work.

Table VII relates to the prescription “use visual management for the identification of spaces, resources, and processes”. It is illustrated by five examples (VII.1 – VII.5). The most applicable example (VII.1) suggests using preference cards. These cards present instructions detailing the equipment, supplies, sterile instruments, and operating room setup for a specific procedure according to surgeon´s preferences (Figure 2, left). Clear wayfinding is also highlighted and includes identifying room usage and directions for users through disclosing information progressively instead of providing all directions at once and at a single point (VII.2, VII.3). Example VII.4 involves employing kanban cards that allow an intuitive monitoring of inventory levels of supplies. Moreover, storage and replenishment of surgical items can be supported by labels on the shelves, displaying diagrams and pictures to inform staff of where each item should be placed (Figure 2 - right). The least applicable example (VII.5) refers to safety considerations by placing signage to indicate the use of lasers and x-rays.

Figure 2 – Left and middle: preference card for an arthroscopy surgery used to identify the case cart near the OR (example VII.1). Right: diagrams on shelves to indicate placement of items for each surgery specialty (example VII.4).

Source: The Authors.

Use visual management for the identification of spaces, resources, and processes										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
	VII.1 Preference cards for operating room set up could include BE recommendations - e.g., operating table, trolleys, equipment, and waste bin positions. To arrange the case carts, nurses can use the preference cards as a checklist that can be attached to the cart to signalise the scheduled surgery and the corresponding operating room. (O, I)									
	VII.2 The operating rooms schedule should be displayed in a centrally located dashboard, helping staff to check room allocation. In nursing stations, there can be a board at the desk to quickly identify the patient's name and location according to the disposition of the bays and the list of day surgeries. (O, I)									
	VII.3 To facilitate hospital wayfinding, the number of decisions required by users should be minimised, with progressive information disclosure, at the right time and order. Demarcating boundaries of different units and including singular elements are also strategies to reinforce people's mental maps. In restricted areas such as sterile corridors, visual signage must be provided – e.g., red lines in the floor. (I, R)									

	VII.4 Shelves can have diagrams or pictures to inform staff. Storage can be managed by kanban systems – i.e., cards for visual and quick identification of replenishment order points. When store persons fill the shelves, barcodes can be scanned, and when a minimal inventory level is reached, it automatically orders a purchase. (O, I)									
	VII.5 Outside signage should be incorporated indicating when lasers and x-rays are used in the operating room – e.g., blinking lights - so staff should wear PPE to access or wait for the lights to turn off. (O, R)									
	Total of practical examples per areas/flows									
	2	**3**	**1**	**5**	**2**	**5**	**1**	**3**	**2**	**1**

Table VII – Practical examples associated with the design prescription "use visual management for the identification of spaces, resources, and processes".

Source: Authors own work.

The prescription "provide slack resources to cope with disruptions" is associated with twelve examples (VIII.1 – VIII.12), in Table VIII. The most applicable example (VIII.1) relates to the role of people as a backup to signage in wayfinding. Also, BE preparedness for emergencies or pandemics is encompassed by several examples. For instance, BE adaptability to different types of uses (e.g., support areas that can be used for perioperative services) should be anticipated in design (VIII.7, VIII.8, VIII.10). Moreover, integrating emerging technologies requires spare points to connect devices expected to be released in the near future (VIII. 9). The least applicable example (VIII.12) suggests allocating PACU patients between empty beds. It facilitates monitoring of patient conditions by the nursing station.

Provide slack resources to cope with disruptions										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**VIII.1** People can play the role of slack resources when the BE configuration is not ideal. For example, if the pathology lab is far from the surgical service, one staff member can wait for the pathology courier to pick the specimen in the surgical service. In wayfinding, staff can complement signage with verbal instructions or guide patients to their destinations. (O, I, R)									
	VIII.2 Positive distractions mitigate stress for users, providing a welcoming environment – e.g., greenery and external views, decoration, artwork, colours, music, balconies to get fresh air in the staff room. Windows with blinds can be designed in the corridors for staff well-being. In operating rooms, windows must have blinds to control light and glare. (O, I, R).									
	VIII.3 Place acoustic barriers when noisy equipment is close to patient bays, as this can increase anxiety and discomfort. (I, R)									
	VIII.4 Anticipate the need for expansion – e.g., extra inventory spaces. (I, O, R).									
	VIII.5 In case of fire, sufficient time for evacuation should be provided by delaying the fire and smoke propagation – e.g., resistance ceiling and floor, and dividing treatment areas with smoke-proof walls. Evacuation routes should have manual emergency call points. Slack areas should be designed on the safe									

	side of the fire wall to accommodate people. The air handling system must be designed for the extra heat load of IT and medical imaging equipment. (R)									
	VIII.6 In energy shortages, back-up power systems must be activated, and each operating room must be provided with an uninterruptible power supply for critical equipment. (R)									
	VIII.7 Plan multiuse spaces, including support areas that allow conversion to perioperative service – e.g., patient bays adjacent to the intraoperative area can be converted into operating rooms or be temporarily used as storage. (O, I, R)									
	VIII.8 If there is no ICU bed available, patients can be transferred to PACU in a bay that should incorporate some ICU resources by adapting the BE. Alternatively, a "high-dependency unit" can be designed to provide intermediate care between PACU and ICU. (O, I)									
	VIII.9 Provide spare connection points to incorporate emerging technologies that may need larger spaces. The anaesthetic machine is a long-lasting investment and might need to incorporate tablets for access to digital records that is a new process. (I, R)									
	VIII.10 Trade-off between dedicated operating rooms and flexible operating rooms. In smaller services, flexibility could outweigh the benefits of specialization. If flexibility is needed, operating rooms layout needs to be free from structural interference and induction rooms can have sliding doors to provide larger operating rooms. Note that flexibility can also cause disruptions - e.g., microscopes in the ophthalmological operating rooms hinder the workflows of other specialties. Either way, operating room setup can differ even for the same specialty, according to surgeons´ preferences – e.g., sometimes they want the machine in a specific location even if cables are in the way. (O, I, R)									
	VIII.11 For all patients, preoperative bays should accommodate family members. (O, I, R)									
	VIII.12 When allocating recovery bays, the PACU leader must be sure that patients have an empty bay between them so a nurse can oversee two patients side-by-side. (I)									
	Total of practical examples per areas/flows									
	5	**7**	**7**	**7**	**7**	**5**	**8**	**1**	**1**	**1**

Table VIII – Practical examples associated with the design prescription "provide slack resources to cope with disruptions".

Source: Authors own work.

Table IX presents ten practical examples (IX.1 – IX. 10) associated with the prescription "design for the prevention of infections and contamination". Corresponding examples refer to air-handling systems (IX.1, IX.6), furniture, fixtures, and equipment (IX.2), layout that allows grouping of patient cohort and separation of flows (IX.3. IX.4, IX.7), materials and finishes that make it easier cleaning and maintaining (IX.5), storage and manipulation of sterile instruments and materials (IX.6), protocols for maintaining a sterile environment, and waste management (IX.8 - IX.10). The most applicable example (IX.1) highlights the importance of air-handling systems in the operating room, which should be the most sterile environment in the surgical service. The least applicable example (IX.10) underscores the specificities of waste and flows and disposal of used instruments in the support areas.

Design for the prevention of infections and contamination										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples										
IX.1 All operating rooms should maintain temperature, humidity, and ventilation acceptable for infection prevention – e.g., positive air pressure with ultra-clean HEPA-filtered air handling systems. Each operating room must have separate exhaust systems to reduce the risk of airborne spread. (R)	■	■	■		■	■	■	■		
IX.2 Dispensers and PPE should be distributed consistently with ease of access across the service. Curtains in patient bays should not touch the floor to avoid contamination. Waste bins should be non-touch, and mirrors may only be installed where hair touching does not compromise infection control and can help check cap and mask donning – i.e., near PPE and scrub bays. (O, R)	■	■	■	■		■		■		■
IX.3 Operating rooms should have enough space for manoeuvring without contaminating the instruments in the sterile field, whose boundaries can be demarcated by led lighting in the ceiling and colours in the floors (O, I).		■				■	■		■	■
IX.4 Robotic surgeries should be allocated in larger operating rooms, as they require a specific surgeon workstation and more instruments and people, which can compromise sterility due to proximity. (O, I, R)	■	■	■		■	■				
IX.5 Joints between finishes and gaps should be sealed – e.g., operating rooms walls should be finished with vinyl at full height. Design slip-resistant vinyl finishes with sealed joints and skirtings throughout the surgical service, especially when fluids are used, or blood splits can occur. (I, R)	■	■	■	■						■
IX.6 Sterile storage areas should have air quality equivalent to the operating rooms, with HEPA filters and shelves at least 30 cm above the floor. A colour scheme can signalise the weight of sterile packs for manoeuvring to avoid holes or falls that compromise sterility during transport and storage. (O, I, R)				■		■	■	■	■	
IX.7 Changing rooms must be designed with two doors, according to staff flows: from semi-restricted areas to restricted areas. Similarly, contaminated areas should ideally have two accesses: an internal door through which the orderlies put the case waste and an external door for the back-of-house corridor where the housekeepers pick and take them to the hospital waste management room. (O, I, R)				■		■				■
IX.8 Give visibility to sterile zones as much as possible such as by using disposable drapes to cover the operating table, trolleys, light handles, and robot arms. (O, I, R)		■				■			■	
IX.9 Corridors of the whole surgical service must have power plugs to enable cleaning. (O, I, R)		■			■					■
IX.10 Disposal of used instruments should avoid occupational risks – e.g., sharp containers should contain indications. Clean utility rooms should be provided and dirty utility rooms for safe disposal of fluids. (O, I, R).				■						■
Total of practical examples per areas/flows	**4**	**7**	**4**	**5**	**3**	**7**	**3**	**3**	**3**	**6**

Table IX – Practical examples associated with the design prescription “design for the prevention of infections and contamination”.

Source: Authors own work

The prescription “use technologies supportive of safe, efficient, and flexible workflows” (Table X) encompasses eight examples (X.1 – X.8). The most applicable example (X.1) highlights the importance of automatic doors in high-traffic areas. In these areas, anticipating patient needs during admission minimizes patient handling and corridor clutter (X.2). Further, installing multifunctional crash rails with handrails promotes safety in common areas and corridors (X.4). High-traffic areas can also have cloud-based digital wayfinding and assistive technologies to enhance navigation with updated information (X.7). In storage areas, dedicated lifts facilitate the transfer of sterile and contaminated items, enhancing infection control (X.3). Also, effective inventory management systems enhance resource allocation (X.5). In the operating room, call systems can support the surgical team to obtain assistance from support areas (X.6).

Use technologies supportive of safe, efficient, and flexible workflows										
	Areas				**Flows**					
	Preoperative	**Intraoperative**	**Postoperative**	**Support**	**Patient/ family**	**Staff**	**Equipment**	**Supplies**	**Sterile instruments and materials**	**Waste**
Practical examples	**X.1** Doors may open automatically in high-traffic areas - e.g., between operating room and induction room. Such doors may have a manual override device in case of emergencies. (O, I, R)									
	X.2 The need for specific patient stretchers could be anticipated in the admission to reduce patient handling and stretchers in corridors. For instance, if a bariatric patient is admitted, a larger bed should be provided in the preoperative phase. Likewise, the need for high mattresses, ceiling-mounted lifting equipment, and large slings can be identified early. (I, R)									
	X.3 Sterile unit should have two dedicated lifts connected with the surgical service: a clean lift for sending out sterile items and a dirty lift to receive the used items. A mistake-proof device can be included in these lifts to prevent the trolley from moving and damaging sterile packs – e.g., a bar to be pushed against the trolley. (O, I, R)									
	X.4 Wall and corner protection is needed in the surgical service common areas and corridors due to the high flow of trolleys and equipment. (R)									
	X.5 In the storage rooms, mistake-proof devices can avoid placing small items behind big ones. (I, R)									
	X.6 Provide call systems with buttons inside operating rooms to signalise the supporting areas that orderlies and clinical staff are needed. Similar devices could be implemented to communicate to the surgical team that the patient waiting in the induction room is ready to enter the operating room. (O, I, R)									
	X.7 Use cloud-based digital signage to allow for the customization of information, such as preferred language and current use of spaces. Also, digital wayfinding can display the distance to a destination, contributing to reducing visitors´ anxiety. (R)									

	X.8 Workstation-on-wheels support ancillary tasks to be completed in surgical downtime, such as checking emails and paperwork. (O, I, R)									
	Total of practical examples per areas/flows									
	2	**4**	**2**	**6**	**5**	**3**	**5**	**2**	**1**	**1**

Table X – Practical examples associated with the design prescription "use technologies supportive of safe, efficient, and flexible workflows".

Source: Authors own work.

5. Discussion

This surgical service study indicated that the design prescriptions served as a data analysis template for the development of new BE design knowledge, expanding the original scope of logistics inter-hospital units explored by Ransolin *et al*. (2024). This new knowledge focuses on logistics intra-hospital units, more specifically corresponding to practical examples applicable to perioperative and support areas of surgical services, and their association with service flows. Thus, the prescriptions are concerned with major themes in the BE design supportive of internal logistics and resilience in hospitals. Moreover, the new design knowledge stresses activities and areas beyond the operating rooms, in which the main value-adding activity of the surgical service takes place. Both in healthcare and in other industries, support flows and corresponding areas are often those in which a large number of improvement opportunities might be identified (Copeland and Chambers, 2017; Moons *et al*., 2019). This study clarifies the need for a systems perspective when analysing the BE of surgical services that are not limited to the operating rooms, the unit of analysis of several prior works (e.g., Neyens *et al*., 2019; Taaffe *et al*., 2023). At the studied service, operating rooms accounted for only 21% of the total floor area. By contrast, the support areas where most logistics processes took place consisted of 61% of the floor area. Moreover, 28 examples focused on the operating rooms (intraoperative areas), while 46 examples were related to the support, pre and postoperative areas. These findings can stem from both the much larger areas outside the operating rooms and the possible wider variety of activities that occur in these areas, which give rise to more variabilities that trigger RP. These results reinforce the need for RP in the internal logistics of hospitals (Göras *et al*., 2019), revealing that logistics within hospital units might be as relevant as logistics between units.

The systems orientation of the developed design knowledge is evident in the nature of the examples related to the prescriptions. For instance, examples IV.1 and IV.4 are mostly socially-oriented, avoiding mixing patients from distinct perioperative phases and with equipment, and sterile and dirty flows. These issues are influenced by technically-oriented examples (e.g., IV.5 and IV.6), which advocate for adequate dimensions of corridors and doorways and plain floor finishes. The prescriptions themselves are also inter-related. For instance, the prescription related to centralisation and decentralisation of resources impacts the walking distances within the surgical services, influencing the prescription of designing routes between perioperative phases. Also, some of the examples of technologies supportive of workflows (e.g., two lifts at the sterile unit) play a role as slack resources.

The design knowledge might enhance the four potentials of resilient systems, namely monitoring, anticipating, responding, and learning (Hollnagel, 2017). This connection can be exemplified based on the recurrent theme of crossings between the flows of dirty items and patients. For instance, when responding to a situation where a lift is out of service, patient flows need to be prioritised over the dirty flows - indicated in example VI.7, on the use of signage for patient-dedicated use. In addition, staff members can provide information and act as slack resources to wayfinding, as indicated in the prescription of slack resources (example VIII.1). In this scenario, monitoring can relate to example VI.2, concerned with managing dirty item flows, especially in single corridor layouts. These flows can be monitored with the support of wayfinding strategies – e.g., VII.3 and X.7, respectively, addressing the use of digital wayfinding to track flows in real-time. Anticipating crossing flows is related to example IV.1, concerned with conducting mock-ups to verify these flows in practice. Learning might result from the continuous updating and refinement of the design knowledge, as well as from the feedback from users of the BE.

The proposed design knowledge can also be analysed in light of the micro, meso, and macro levels of health services, which is a commonly adopted analytical framework in the resilient healthcare literature (Berg *et al*., 2018). The design of resilient systems tends to benefit from explicitly interrelated designs at all levels (Disconzi and Saurin, 2024). This study can be positioned primarily as a contribution to the design of resilient systems at the micro level. Indeed, despite the significant area, the surgical service is one of several hospital units and occupies only 10% of the total hospital area. There are secondary implications at the meso level, related to the interactions between the surgical service and other units. These were visible, for instance, in all examples related to instruments that move from the sterile unit to the surgical service and then back. At the macro level, regulations could make it explicit that certain requirements are particularly important to support RP. Regulations might be assets for resilient healthcare as they promote designs and structures for RP across health systems (Øyri and Wiig, 2022; Macrae, 2019).

Figure 3 summarizes the main relationships between the elements of the proposed design knowledge. It depicts the connections between the BE knowledge levels (i.e., prescriptions and examples), application focus (i.e., BE areas and workflows), and RP as the end goal of using such knowledge. This Figure also highlights the emergent nature of RP (Wachs *et al*., 2016), arising from the interactions between the BE and workflows. The logical connections between the prescriptions and RP, referred to in Figure 3, were presented in Table I.

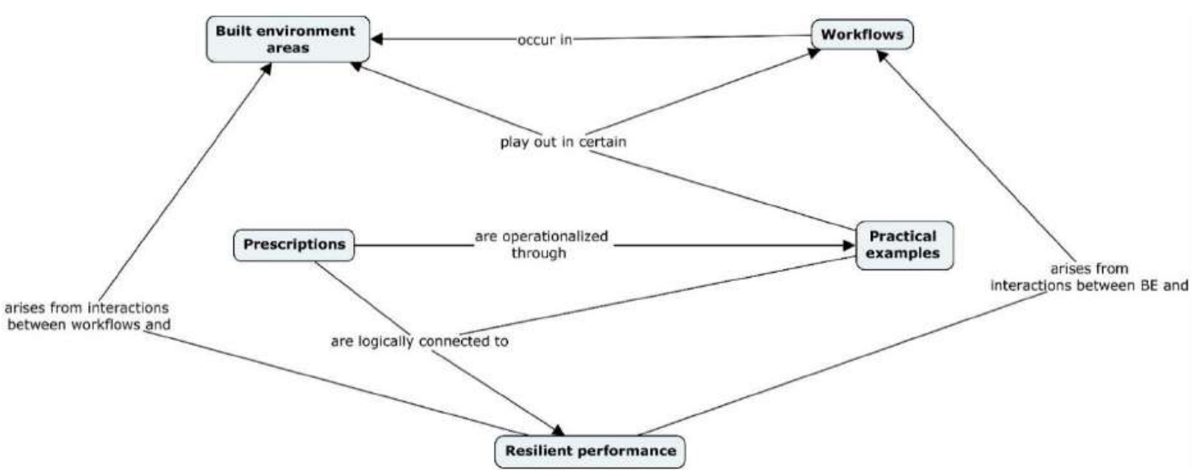

Figure 3 – Relationships between the elements of the proposed design knowledge.

Source: Authors own work.

Additionally, Figure 4 conveys how the design knowledge applies to a generic surgical service. In the middle, this figure refers to the design knowledge, which is applicable to perioperative (preoperative, intraoperative, postoperative) and support areas, besides six service flows (patient/family, staff, equipment, supplies, sterile instruments and materials, and waste) that support the surgical activities. Patient and family flows occur mainly in the perioperative areas, while the other service flows take place, at least partly, in the support areas.

The prescriptions were relevant to all studied service flows, thus probably being of interest to surgical services other than the one studied. The practical examples are also of general interest, although their scope of application is relatively more context-dependent. Although such contextual influences make any generic prioritisation elusive to some extent, we suggest that all prescriptions and examples with direct implications to the safety and well-being of patients and providers take priority over the others. Stakes are high in these settings, and patient-centred models of care provision have been widely recognized as crucial (Acher *et al*., 2015; Rosa *et al*., 2018).

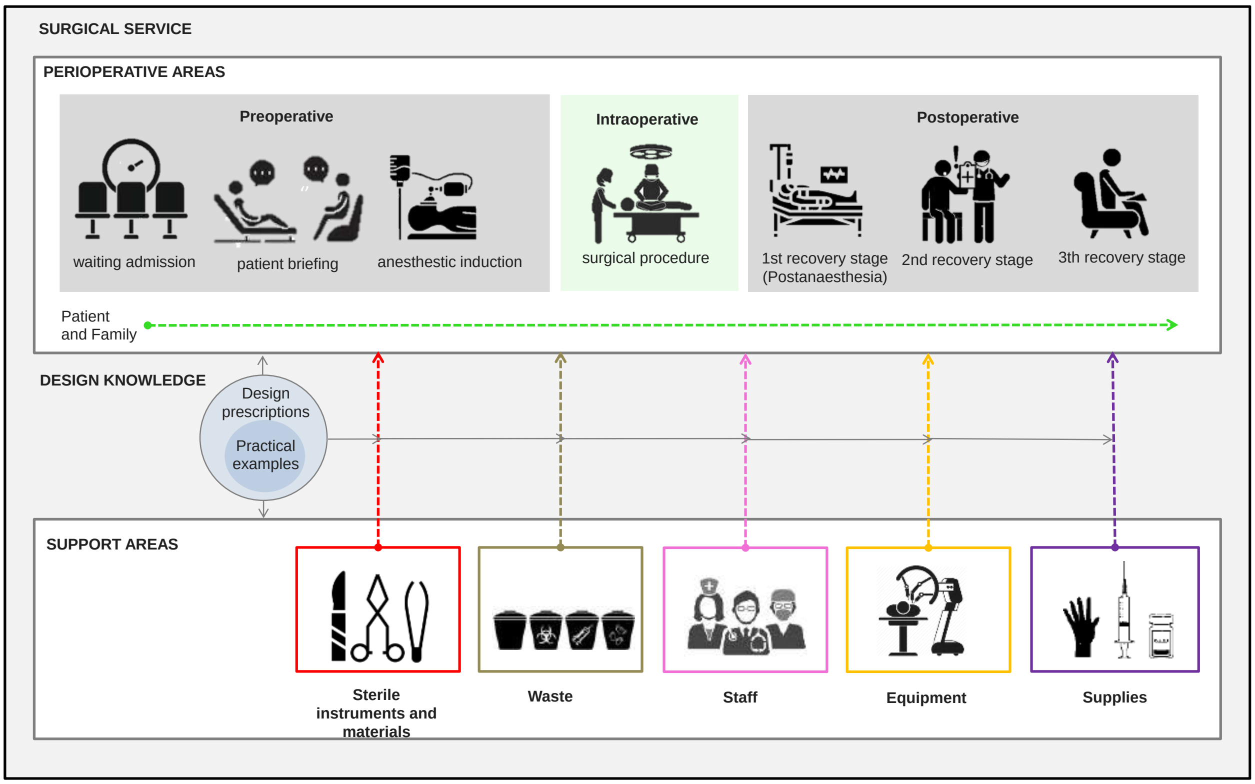

Figure 4 – Schematic representation of how the design knowledge applies to a generic surgical service.

Source: Authors own work.

Finally, it is worth noting that the neglect of the design knowledge can hinder not only RP but also other performance dimensions of surgical services such as safety and efficiency. Neyens et al. (2019) and Wahr et al. (2013) reported that layout and equipment positioning significantly influenced disruptions in the operating room, creating risks of surgical site infections. In this regard, example VI.3 (prescription 'give visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility') highlights strategies to avoid clutter and risks of slips, trips, and falls – e.g., power plugs evenly distributed to reduce the use of cords and cableless equipment. Moreover, example VIII.9 (prescription 'provide slack resources to cope with disruptions') refers to equipment´s connection points to incorporate emerging technologies, which if not well integrated with existing systems can contribute to errors due to the need to constantly switching tasks and equipment (Jurewicz et al., 2021). As a more general consideration, Rapport et al. (2020) reported the negative impacts of unfit-for-purpose workspaces on the work and well-being of surgical staff and patients.

6. Conclusions

The research question that guided this study was concerned with how to develop BE design knowledge supportive of RP in the internal logistics of surgical services. A case study of a surgical service indicated that the prescriptions adopted as a point of departure effectively served as a data analysis framework to answer the research question, addressing a variety of interactions between the areas and workflows of surgical services. Thus, the new design knowledge, highlighted in Tables IV to X, is composed of seven prescriptions slightly reworded in relation to their original version by Ransolin et al. (2024), 60 new practical examples, and their association with six workflows (i.e., patient/family, staff, equipment, supplies, sterile instruments and materials, and waste) and two major areas (perioperative and support). This is a systems perspective that considers areas and flows that play out outside of the operating rooms, the main unit of analysis of prior studies of BE in surgical services. Connections with resilience engineering were made explicit in the rationale for the prescriptions and when linking the findings to the four resilience potentials and the micro, meso, and macro levels of healthcare systems. For practitioners, the design knowledge is valuable for BE designers, hospital managers, and regulators interested in highlighting requirements supportive of RP.

Limitations of this study should also be acknowledged. First, findings resulted from the case study of a private medium-sized hospital, which is a setting with relatively fewer complex flows than larger and public hospitals where greater variety of patients and processes are likely to be found. Second, the prescriptions were not implemented during a new BE design or intervention of a surgical service. Third, depending on organisational factors (e.g., budgetary limitations), it might not be possible for all prescriptions to be implemented. Fourth, indoor environmental quality factors were not explored in depth, even though they were addressed by some practical examples – e.g., example VIII.2 mentions the need for blinds in the operating room windows to control light and glare; VIII.3 advises acoustic barriers in patient bays, and 43 recommends that all operating rooms should maintain temperature, humidity, and ventilation acceptable for infection prevention.

This study gave rise to opportunities for future studies, as follows: (i) implement the design knowledge in the redesign of the studied surgical service and others; (ii) adapt or develop new design knowledge for other health services; (iii) investigate how the design knowledge can contribute to improve regulations and good practices in BE surgical service design and operations; (iv) investigate the interactions between the surgical service flows and broader health services, along with BE implications – e.g., staff flows to and from the hospital warehouse and sterile unit; (v) contrast different sites and settings in a larger, longitudinal study with an international focus; and (vi) develop a method for assessing the extent to which the design knowledge is used by surgical services, also shedding light on the qualitative and quantitative impacts of using (or not using) it.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX K – Supplementary Material (Paper III)

Supplementary Material: illustrations of practical examples, based on the case study

Design prescription: **Design safe, efficient, and flexible routes between perioperative phases** (practical example IV.2)

IV.2.

Width of internal corridors to store case carts, patient beds, and supplies.

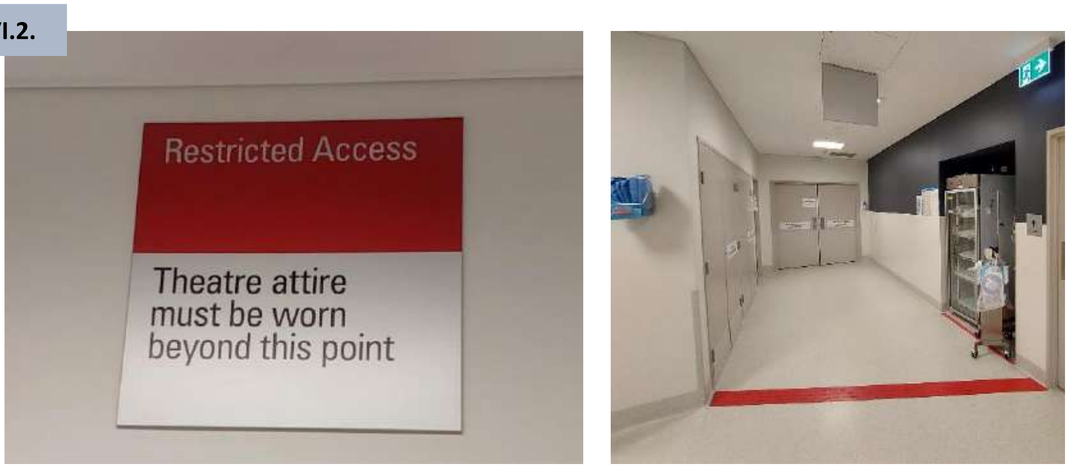
Design prescription: **assess the pros and cons of centralisation and the decentralization of resources** (practical example V.11)

V.11.

Scrub bay and induction room that can be shared between operating rooms.

Design prescription: **Giving visibility to flow interferences, obstacles, and risks that hinder safety, efficiency, and flexibility** (practical example VI.2)

VI.2.



Visual demarcation prevents people from crossing restricted areas before donning theatre attire.

Design prescription: **Use visual management for the identification of spaces, resources, and processes** (practical example VII.4)

Design prescription: **Provide slack resources to cope with disruptions** (practical example VIII.7)

VII.4.

Storage room has diagrams of different surgical cases attached to the shelves to inform staff.

VIII.7.

Perioperative patient bay is being temporarily used as equipment storage.

Design prescription: **Design for the prevention of infections and contamination** (practical example IX.3)

IX.3.

Operating room has sterile field boundaries demarcated by led lighting in the ceiling and colours on the floors.

Design prescription: **Use technologies supportive of safe, efficient, and flexible workflows** (practical example X.6)

X.6.

Operating room with buttons to signal to the supporting areas that orderlies and clinical staff are needed.