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Congruence Mapping of the Activity Flows Allocated in Built Environments: A Pilot Application of Under-Development Software in an Emergency-Care Service

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Featured Application: This paper presents the application of a software program that is currently under development that provides feedback for the mapping activities that are carried out in built environments and analyses the congruence in the relationship between the flow of activities and their environments. Exemplary results were obtained in the case study of a healthcare emergency facility, although it is possible to apply this software in other types of complex environments. The obtained data allow facility managers to prioritize and reallocate activities when a change is required. It also shows unmapped relationships. It is important to investigate these data because they can indicate failures in the mapping process and can provide an opportunity to obtain a more complete understanding of the allocation and flow of activities. These data can also help us to identify points of conflict or opportunities for adjustment in the allocation of activities in order to improve the flow of activities.

Abstract: Due to the large number of activities that must be carried out by emergency-care services (ESs), the tasks of facility managers and architects are challenging and complex. Several strategies, guides, and diagnoses have already been developed in order to improve ESs. Part of the solution to this problem depends on obtaining a normative and universal understanding of the problem, and another part depends on conducting a specific and relational analysis between the environment and the flow of activities that are allocated within it. This paper presents the results of a study that was conducted using a software program that is currently under development for mapping the congruence relationship between activities and environments. Here, we present a discussion of the first results that were obtained with the instrument, which was applied to a single case. For this purpose, the fundamentals of the instrument, as well as the environment and the flows of an ES at a university hospital, are described. The forms of analysis, benefits, and limitations of the instrument were investigated, with a view towards its use in supporting the management and the design of large and complex environments, such as emergency departments. In this program, the relationships that are hidden from the managers, the designers, and the researchers due to the aforementioned complexity are revealed through the use of matrices. This mapping can supplement the decision making of the managers and the designers. The application showed advantages in modeling with fewer inputs, mainly in pre-design evaluations.

Keywords: congruence mapping; flow of activities; environment allocation; evaluation method; data analysis; evidence-based design (EBD); post-occupancy evaluation (POE); pre-design evaluation (PDE); design structure matrix (DSM); open source

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1. Introduction

The planning, design, and facilities management processes in large, dynamic, and complex installation facilities, such as healthcare facilities, are continually evolving [1–3]. The emergency department (ED) is the most vital and complex sector of any healthcare facility [1,4], representing a "front door" for primary care hospitals, through which most inpatients enter the hospital [1,2]. Inadequacy in the flow within the ED has the potential to impact the hospital system's functions and hamper the overall delivery of the health services [1,2,4]. Thus, it is important to have the means to carry out building performance evaluations and interventions based on evidence and inventiveness.

Evidence-based design (EBD) allows for the improvement of the design decisions for planned or existing environments [3,5,6]. Research that is oriented toward design and facility management (FM) has also focused on mapping, modeling, and simulating the building performance [7], behavior [8,9], and organization [10], the allocation of resources [4,11], the flow of people and activities [9,11], the operational efficiency [12,13], the space and layout [14,15], and the optimal paths [16]. Among the existing modeling, simulation, and evaluation methods, there is a lack of straightforward and logical resources that can be used to assess whether the allocation of activities in a built environment is congruent. Mapping the flow of activities in order to support the allocation of services in a healthcare facility can provide a source of robust information in order to support the facility's management and design. In this study, we present the application of a software program that offers the means to accomplish this task.

In this study, an activity flow and allocation problem, which was observed in a real-life case in the form of a single pilot case study, guided the development of a method for mapping allocated activity flows. This method provided the basis for an open-source mapping software that is currently under development, which is called Multidomain Congruence Mapping and Simulation (MC-MS), the fundamentals of which are presented in Section 2, below. The results of this study focus on the functionality of the software's methods and procedures, and do not cover aspects of the software's usability. We present the matrices that have been derived from responses to a survey and examine how the congruence between the flow and the environments was analyzed.

1.1. Challenges and Complexities of Emergency Departments

Recent studies have reviewed the evidence demonstrating the impact of healthcare facilities on patient outcomes [1,17]. Others have pointed out that healthcare workers exhibited reduced efficiency when they were performing their tasks in unsuitable working environments [15,16]. In particular, a problematic ED design can have a potentially detrimental effect on patient and staff health, safety, and satisfaction, leading to contamination, and crowding issues [1,5,18,19]. Unfortunately, reports of EDs with long waiting times, busy staff, and crowded and uncomfortable rooms are recurrent [1]. Brambilla et al. gathered detailed information on ED operations from medical, economic, social, managerial, technological, and statistical perspectives, while paying less attention to the relationship between the ED layout and its functional interactions with emergency-care services (ESs) and hospital support services [1]. Focusing on hospital facilities in general, several studies have discussed the design attributes of healthcare environments with the aim of making them more effective [5,20], investigating aspects such as the circulation conditions in relation to users' perceptions and experiences [21], infection control [5], and logistics [11].

In regard to contamination risks—a discussion that has been aggravated by the COVID-19 pandemic—the literature suggests that the design of the environment strongly affects hospital infection rates, due to cross-contamination [5,22]. Even before the sanitary emergency of COVID-19, several studies addressed the issues that are related to the flow of activities in order to improve healthcare conditions, focusing on the circulation [21,23], the waiting times [24], crowded patient environments [18], transport, and the storage of materials [11]. From a logistical perspective, effective hospital design can improve the flow of materials, reducing valueless activities and the activity time that is linked to the unavailability of adequate environments and infrastructure [11]. While one study recommended compartmentalization and ambiguity in regard to circulation, another study suggested a reduction in displacement and deposit distances. These are distinct, and sometimes contradictory, demands that illustrate how the overlapping flows of healthcare and support activities add complexity to the design and the operation of hospitals.

In recent decades, post-occupancy evaluation (POE) and other performance evaluation methods have been used to analyze several healthcare environments, consolidating detailed information that supplements the standardization and the EBD of new and better healthcare environments [20]. These inductive and normative approaches, however, show a limited scope in assessing the adequacy of new design solutions to solve the emerging problems. This difficulty was clearly observed as hospitals struggled to adequately respond to the demand for emergency and intensive care unit (ICU) beds at the scale of and within the timeframe that was imposed by the COVID-19 pandemic [22]. Designers, facilities managers, and health workers found difficulty in evaluating the complexity of the situation based on their perceptions and in carrying out adjustments in the allocation of activities related to the healthcare services that they offer [5,25]. These difficulties, however, are neither new nor unique. They can be mitigated by using decision support methods and instruments.

1.2. Pre-Design Evaluation (PDE), Models, and Performance Simulations

Although facility management and healthcare facility design are strongly supported by reference standards and guidelines, benchmarks, and checklists [1,26], there are contextual features that need to be considered. Since each design problem is unique, the demands for better designs require a personalized approach, in which the solutions are individually evaluated even when they are based on standards and benchmark studies [27]. In order to evaluate the adequacy of these aspects, it is preferable to consider the key performance indicators (KPIs) that are associated with descriptive techniques [28]. These descriptive techniques can take the form of analytical approaches, simulations, and statistical/empirical modeling [28,29]. The approaches that are adopted are related to the model's complexity and processing capacity, and the skills that are needed to operate the model [7,26].

Simulation models emulate the approximate behavior of real systems in great detail. They can be used to model discrete events or system dynamics, or they can be used in agent-based modeling [28,30]. However, a realistic simulation requires a balance of probability distributions and an accurate and meaningful input dataset [28,31], which can be obtained through sensors [9]; georeferencing; a global positioning system (GPS), which is used to create hourly routine snapshots of all tagged individuals [12]; and so on. Different models have been applied in order to analyze the mapping of the workflow and the allocation of activities in built environments [12,27,32,33], as well as for other applications, such as generating floorplan layouts [32,34,35], lighting simulations [36,37], analyses of visual quality [38], behavior prediction [39], determining building envelope costs [40], etc. These simulation models mainly support the design phase when the design demands have been identified and the functional requirements have already been defined.

Statistical/empirical models rely solely on empirical data to estimate the relationship between the system parameters and the performance measures. They require a large amount of detailed data in order to model a scenario that is useful, i.e., statistically valid. This is a suitable approach for formulating and improving sectoral policies, standards, and indicators, such as KPIs [10,28]. The application of these models in single cases, such as a building complex, is less common because the conditions for the operation of such models are available only in restricted socioeconomic, technological, and institutional contexts where massive amounts of data are available, for example, in studies with access to data that were recorded through capture technologies, such as real-time location-based services (RTLS) [2,10,41]. The modeling of single cases without the availability of reliable sampling—that is, in a unique context and with a relatively small amount of data—demands another approach.

Analytical models employ a set of mathematical equations in order to determine the relationship between parameters and the system performance. They are popular methods because they present simple and efficient solutions when they are not used to model stochastic and dynamic systems [28]. The analysis of reduced datasets benefits from the use of this approach. For example, when studying a particular arrangement of activities in an environment in order to support decisions about changes in that arrangement, data collection and analysis need to be fast and accessible. The process must be fast because it is responding to an urgent demand, and it must be accessible so that it can be applied in different contexts.

A lightweight strategy that is adaptable to different data volumes, and that has already been adopted in the development of complex systems, is the dependency (or development or design) structures matrix (DSM) [42,43]. In construction surveys, it has already been used to improve the flow of information [44], to evaluate the building's adaptability [45], to sustainably prolong the building's useful life [46], and so on. The DSM allows us to determine (and describe), through a mathematical matrix, whether the dependencies between the activities in a given complex process have serial relationships, parallel relationships, or if they have iteration relationships between their realization [47]. It is used to optimize collaborative work dependencies in order to reduce iteration and rework and thus improve the collaborative efficiency and optimize resources [46]. Another use of this strategy in architecture, engineering, construction, and maintenance is in improving the architecture of buildings. The DSM is an effective method for illustrating the dependency relationships between components and environments in building architecture [46].

In order to reduce the complexity of the built environment, it is possible to discretize the geometry of the spaces of a given layout in a topological model, which is a graph with spaces as vertex attributes [27,34,46,48]. With the graph matrix of the spatial arrangement, it is possible to relate the dependencies with other matrices through a multi-domain matrix (MDM) [45,49]. This relationship, which recurs in other research areas, such as structural design [46], product design [50], and systems development [51], is the basis of the functionality of the program that is presented here.

1.3. Hypothesis, Main Objective, and Findings

The determination and the analysis of the predictable relationships between the activities of people with different roles in a healthcare setting and their occupied environments allow one to anticipate part of their possible interactions. With this information, managers, architects, and designers can evaluate a given occupation arrangement, create comparative scenarios, and decide on a better allocation solution. The relationships are given importance due to the concepts of centrality and connection.

Therefore, our hypothesis was that it is logically possible to determine if an arrangement has congruence—that is, if the connection and the centrality between activities are more or less near—using, for that purpose, matrix operations to express the relationships between the activities and the environments. Thus, the objective was to develop and test a software platform that allowed the identification of congruent relationships in the allocation of activities in a built environment. This paper presents the results of applying an analytical model that was developed to map the congruence relationships between the flow of activities and the built environment. A discussion is presented of the first results that were obtained with the application of the developed instrument in the case of a single healthcare facility.

2. Materials and Methods

The multiple methods that were employed in this study included approaches based on an analytical model and a single pilot case study.

The analytical model was developed based on a logical structure that has already been demonstrated in previous studies on analyzing and optimizing processes and has been applied by organizations developing complex product systems [43,46,51–54]. The methodological novelty of this study lies in formulating and testing a multidomain complexity mapping system with a focus on FM and PDE, which is called MC-MS. The mapping process considers the following five variables [55]:

- Environment—facilities that are spatially distinct in the building where an actor engages in a healthcare or support activity;
- Stakeholders—people or groups who play a role as demanders of services (patients) or as service providers (health and support professionals);
- Activities—actions performed to obtain an expected result;
- Process—an action chain or steps taken by stakeholders with a well-defined purpose;
- Organization—a structure of rules and available resources to enable processes (roles, environments, and materials resources).

These variables are related to the domains of the environment and activities to support the analysis, as indicated in Section 2.1.

An exemplary architectural decomposition process is presented here with a single case study to demonstrate the application of the analytical model. The physical architecture and operational architecture were decomposed, considering the functional organization of the case study. The organizational variables that do not play a role in ESs were isolated. Regarding the choice of a single case, [56] argued that a real organization—in this case, hospital management—should be involved in the development of the modeling or simulation of the intended design. This engagement reinforces the credibility of the model by indicating users' confidence in the capability of the proposed model [26,56]. Thus, obtaining agreement from the health institution to collaborate with the research was one condition for carrying out this study. Another preliminary condition for the commencement of the research was the approval of the research ethics committee.

Data were collected as indicated in Section 2.2 and the procedures for curation, processing, and visualization are presented in Section 2.3.

2.1. Analytical Modeling MC-MD System Methodology

Based on a method of complex product-systems development, we proposed a structured approach to map, one-to-one [49,57], the instances of congruence between the environment's architecture and the work organization process in an ED.

The mapping of congruence was achieved using the following equation for determining the potential of interactions between the domains [49,52]:

$$eP_{mm} = R^{t}_{mn}.A_{nn}.R_{nm} \tag{1}$$

$$aP_{nn} = R_{nm}.E_{mm}.R^{t}_{mn} \tag{2}$$

where the matrices are identified as follows:

- *eP* – Potential environment relationships matrix;
- *aP* – Potential activity relationships matrix;
- *E* – Environment matrix;
- *A* – Activities matrix;
- *R* – Relationship matrix between environment and activities.

Equation (1) indicates the environmental congruence with the activities, and Equation (2) indicates the congruence of the activities with the environment. The *R*-transposed matrix (R^{t}_{mn}) allows all relationships between environments and activities to be considered even when the other has a different size [49].

The A and E matrices are binary DSMs. A_{nn} indicates if activity j depends on, or is sequential to, activity i; whereas E_{nn} indicates if environment j is connected to environment i. Both matrices accept only 1 or 0 values for yes or no. The R matrix defines the relationship between the environment and the activities; therefore, it is a multi-domain matrix (MDM). This matrix accepts three values (Table 1) to establish strong and weak relationships between each activity and environment. The intermediary activities are carried out to make the end activity possible; end activities respond to service goals and add value.

Table 1. Types of relationships for an activity carried out in an environment.

	No	Processes/Activities
	1	when an actor circulates in the environment j to perform the activity i
	2	when an intermediary activity i occurs in the environment j
	3	when the end activity i occurs in the environment j

Finally, the comparison defines the organizational alignment between environments and activities in the congruence matrices. There are two matrices. The activity congruence matrix (aC) indicates the activities that interact because they occupy the same environment. The environment congruence matrix (eC) indicates environments that have an interface because they accommodate actions that are necessary for an activity (taking into consideration strong interactions).

Three conditions were determined for each comparison matrix, as shown in Equation (3) for environments (eC_{mm}) and Equation (4) for activities (aC_{nn}), as follows:

$$eC_{mm} = \begin{cases} eC_{ij} = 3 & \text{if} \quad E_{ij} = eP_{ij} \\ eC_{ij} = 2 & \text{if} \quad E_{ij} > eP_{ij} \\ eC_{ij} = 1 & \text{if} \quad E_{ij} < eP_{ij} \end{cases} \tag{3}$$

$$aC_{nn} = \begin{cases} aC_{ij} = 3 & \text{if} \quad A_{ij} = aP_{ij} \\ aC_{ij} = 2 & \text{if} \quad A_{ij} > aP_{ij} \\ aC_{ij} = 1 & \text{if} \quad A_{ij} < aP_{ij} \end{cases} \tag{4}$$

These three conditions were used to fill each eC_{ij} or aC_{ij} cell in the congruence matrices. To facilitate understanding and visualization, the values of each cell were represented by a color and its respective meaning (Table 2).

Table 2. The analyzed congruence conditions.

	Nº	Comparative Relationship
	1	i and j relationship not predicted or detected
	2	i and j relationship predicted and unconfirmed
	3	i and j relationship predicted and confirmed

The input data used to relate the activities and environments linked to the ES were treated according to this analytical model. In addition to identifying data from these two domains, stakeholders, processes, and organizations were considered as variables.

2.2. Data Collection in the Case Study

We collected data and information in a single pilot case study of the specific operating conditions of an ES that was allocated in a hospital in order to verify the analysis. The location of the case study was the adult emergency department (AED) of a university hospital, which was built from 1969 to 1978 and inaugurated in 1981. The hospital has six floors and a gross built area of 36,000.00 m^2, 874.88 m^2 of which are AED-occupied. Access to documents, interviews, and technical visits was possible due to the academic cooperation agreement. This allowed the systematization and analysis of unpublished information about the building and its activities and functions. In the data collection process, we considered ESs and support activities for emergency services. In this way, the scope of the survey covered the activities that were conducted on three floors of the hospital.

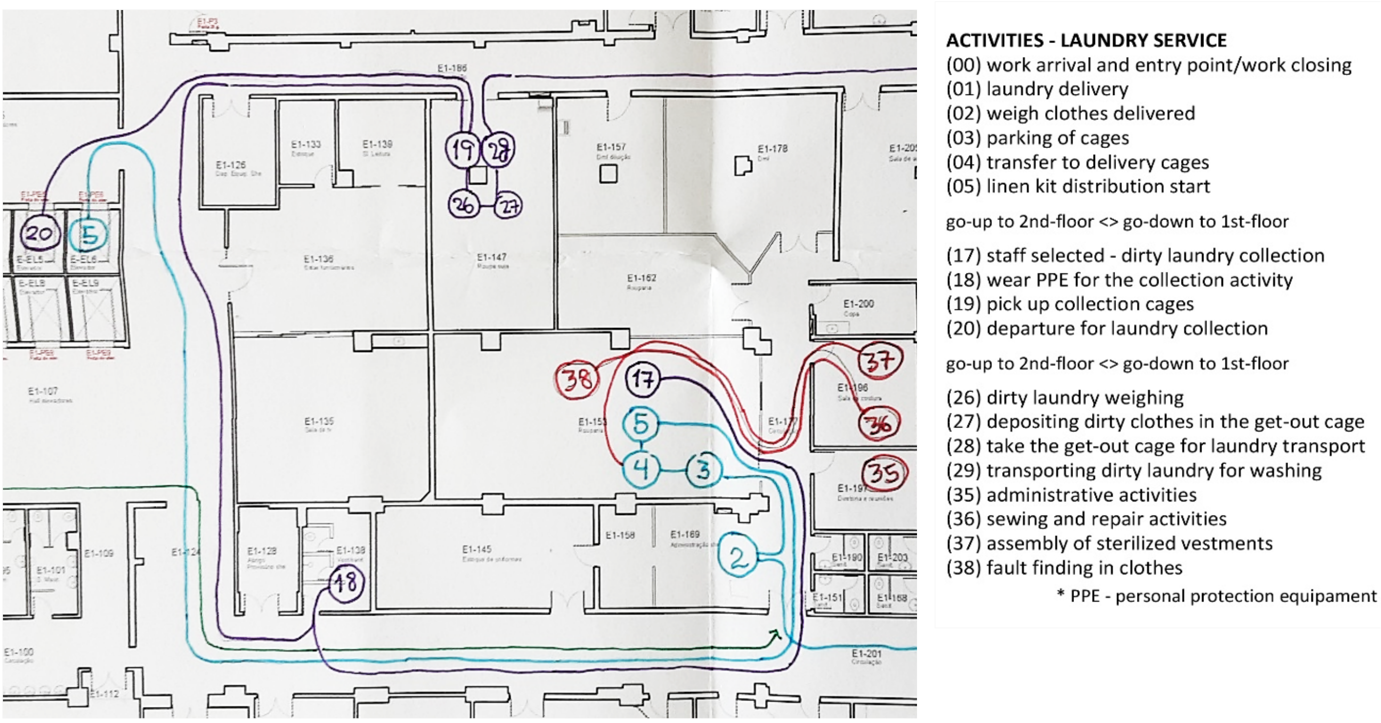
Activity Flow and Allocation Mapping

The environment-functional analysis was carried out by studying the flow of activity and its relationship with the built floors to determine the physical footprint of the departments linked to the ESs [1,20]. The information about the activities was obtained through semi-structured interviews, which were conducted between October 2021 and June 2022, with 13 key healthcare professionals who were highly engaged in healthcare processes (Table 3). The respondents were selected because they occupied management and operational roles. Thus, it was possible to obtain a strategic and practical understanding of the services provided and the relationships between activities. The identification of interviewees was achieved by consulting the board and examining information such as professional training, time in the office, and employee recognition.

Table 3. Interviews designated by the focus on processes/activities.

No		Processes/Activities
1	Emergency	nursing—AED
2		medicine—AED
3		replacement of consumables
4	Pharmacy	analysis of prescriptions and drug interactions
5		prescription analysis and drug distribution
6	Patient host	reception services
7		clinical record services
8	Hospitality	laundry services
9		cleaning services
10		nutrition and food
11		security service
12	Maintenance	building maintenance
13		equipment maintenance

In the semi-structured interviews, the interviewers used a script to address the interviewees. The interviewers could elaborate on the questions based on this script as they obtained responses [58]. The interview dynamic consisted of asking the interviewed healthcare workers to describe the following three aspects of the work for which they were responsible: (a) the routine sequence of activities, (b) the occurrences of interactions with other workers' roles and activities, and (c) the allocation of activities in the floor space, differentiating between whether each activity was a middle or an end activity. The support material consisted of an interview script (S1), a spreadsheet to write down the activities, and floorplans to locate the activities and trace routes (Figure 1). Audio of the face-to-face interviews and the videos of the remote interviews were recorded with the prior authorization of the individual participants.



(**a**) (**b**)

Figure 1. Example of the in-person interview records. (**a**) Plan of the first floor; (**b**) laundry services activity list (translated notes).

Additional information was included subsequently, through observation of the interview records. For example, the relationships between each activity and the people/departmental functions involved were detailed.

2.3. Data Curation, Processing, and Visualization

The records obtained in the interviews were revised and formalized with computer-aided design (CAD) software. Then, these data were compiled to be processed using the analytical model system. Data on the activities, environments, roles, and functions were listed in a *.txt file, adopting a syntactic structure for the notation that was defined in the system development stage (Table 4).

Table 4. Syntactic structure of notation developed for MC-MS reading.

Lists	Syntax Notation	Notation Example
Organization Roles	[SECTOR NAME, in Caps] ↵ [role number] <=> [role naming]	USERS 0001 <=> unclassified patient NURSING SECTOR 1003 <=> nursing technician CLINICAL SECTOR 2001 <=> attending physician
Activities/ Process	[PROCESS NAME, in Caps] ↵ [activity number] <=> [activity description] ↵ → [involved role number 1] ↵ → [involved role number n] ↵ → → [previous activity number 1] ↵ → → [previous activity number n] ↵	ADULT EMERGENCY SERVICE (AES) 1014 <=> adult-emergency spontaneous demand → 0001 1015 <=> spontaneous demand screening → 0001 → 1003 → → 1014 1016 <=> clinical evaluation of the patient admitted

		→ 0001 → 2001 → → 1015
Environments	[SECTOR NAME, in Caps] ↵ [environment. number] <=> [env. description] ↵ → [interfaced environment number 1] ↵ → [interfaced environment number n] ↵	ADULT EMERGENCE DEPARTAMENT (AED) 2015 <=> ambulance stop - direct access → 2001*[1] → 2042 2042 <=> AED access circulation → 2015 → 2043*[1] → 2095 2095 <=> Observation room → 2042 → 2182*[1] 2182 <=> prescription circulation → 2095 → 2125*[1]
Relationships	[activity number] ↵ → [environment number],[relationships value*[2]] ↵	1014 → 2001,1 → 2015,3 1015 → 2015,1 → 2042,3

*[1] Some environment descriptions are not indicated in the example but exist in the real architecture.
*[2] The “relationships value” corresponds to the relationship types of the activity in the environment (Table 1).

The role list was intended to organize the roles. It allowed the identification of the participants in an activity (active or passive). The activities/process list provided input data for the activity matrix (A_{nn}). It was a DSM that offered subsidies for analyzing the managers and teams that were involved in the mapped services. Another DSM of the analytical model, the environment matrix (E_{mm}), was obtained from the environment list data.

The last analytical model matrix that was assembled directly from the data lists was the relationships matrix (R_{mn}). This was an MDM that related the activities with the environments. This matrix indicated an institutionally recognized relationship between the organization’s roles and the environment (Figure 2).

Figure 3 presents a framework of how the analytical model works. The matrix lists E_{mm} and A_{nn} are binary; each cell is either full or empty. For the R_{nm} matrix, we adopted the colors that are indicated in Table 1 to present the relationship results. The matrices eP_{mm} and aP_{nn} are matrices of variable values, which are used for comparisons with matrices E_{mm} and A_{nn}, respectively. For the eC_{mm} and aC_{nn} matrices, we used the colors that are shown above in Table 2.

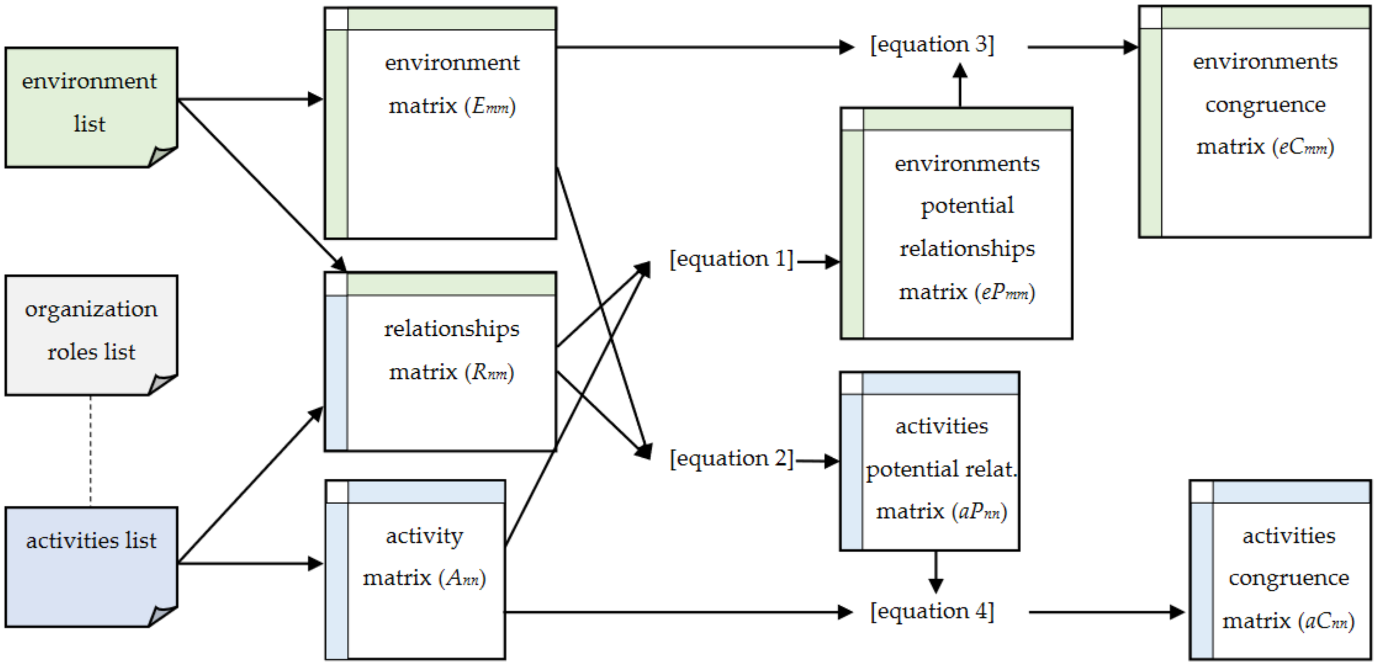
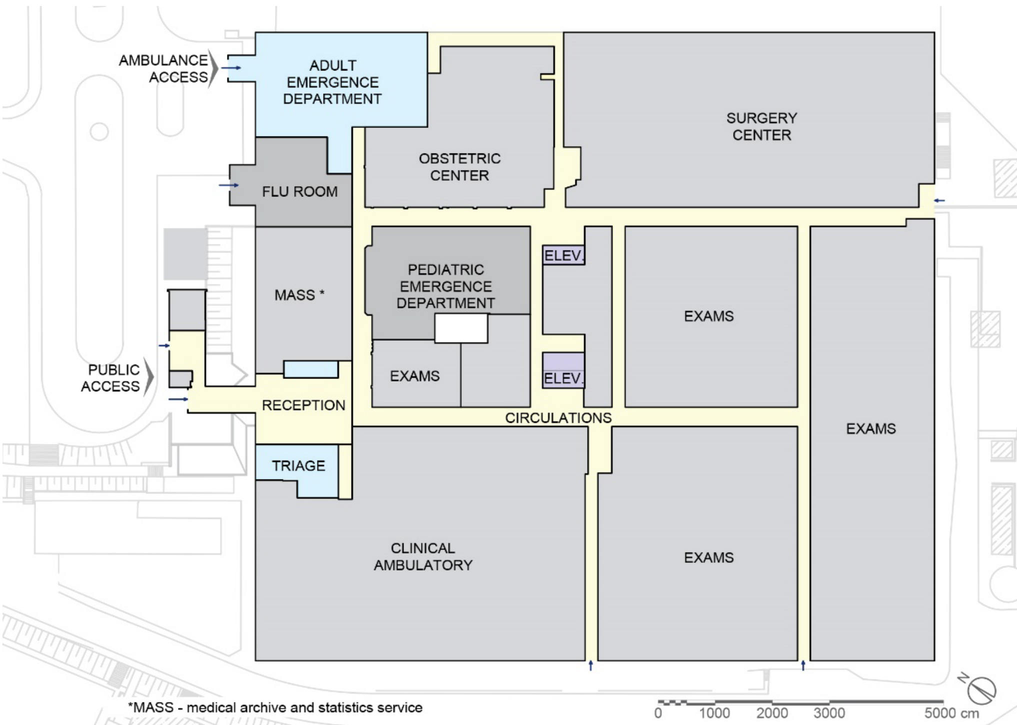
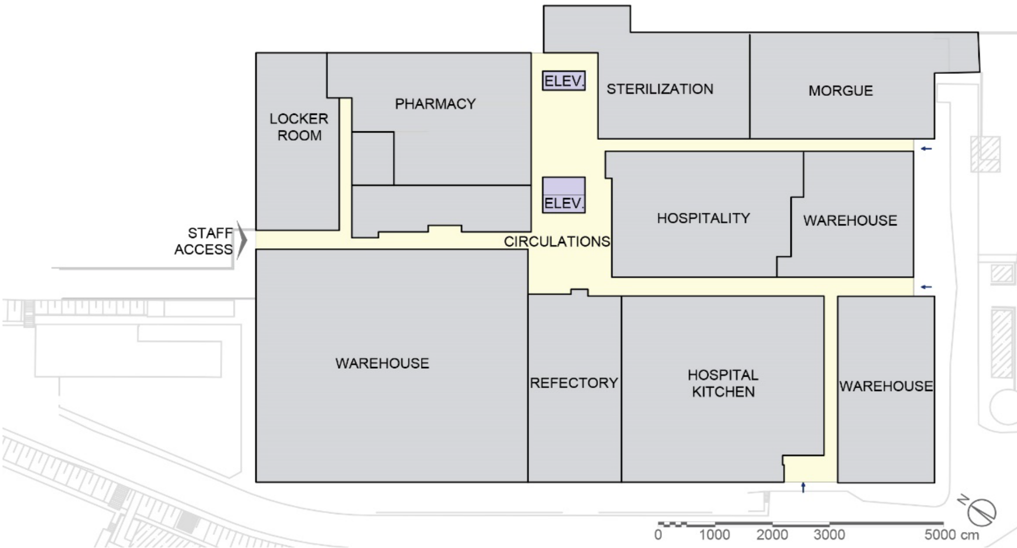


Figure 2. Analytical model framework.



(**a**)



(**b**)

Figure 3. Scheme of the hospital's main sectors. (**a**) Plan of the second floor; (**b**) plan of the first floor—based on *Superintendência do Espaço Físico* (SEF HU USP) files.

2.4. Research Datasets, Ethical Approval, and Use Permissions for Materials and Information

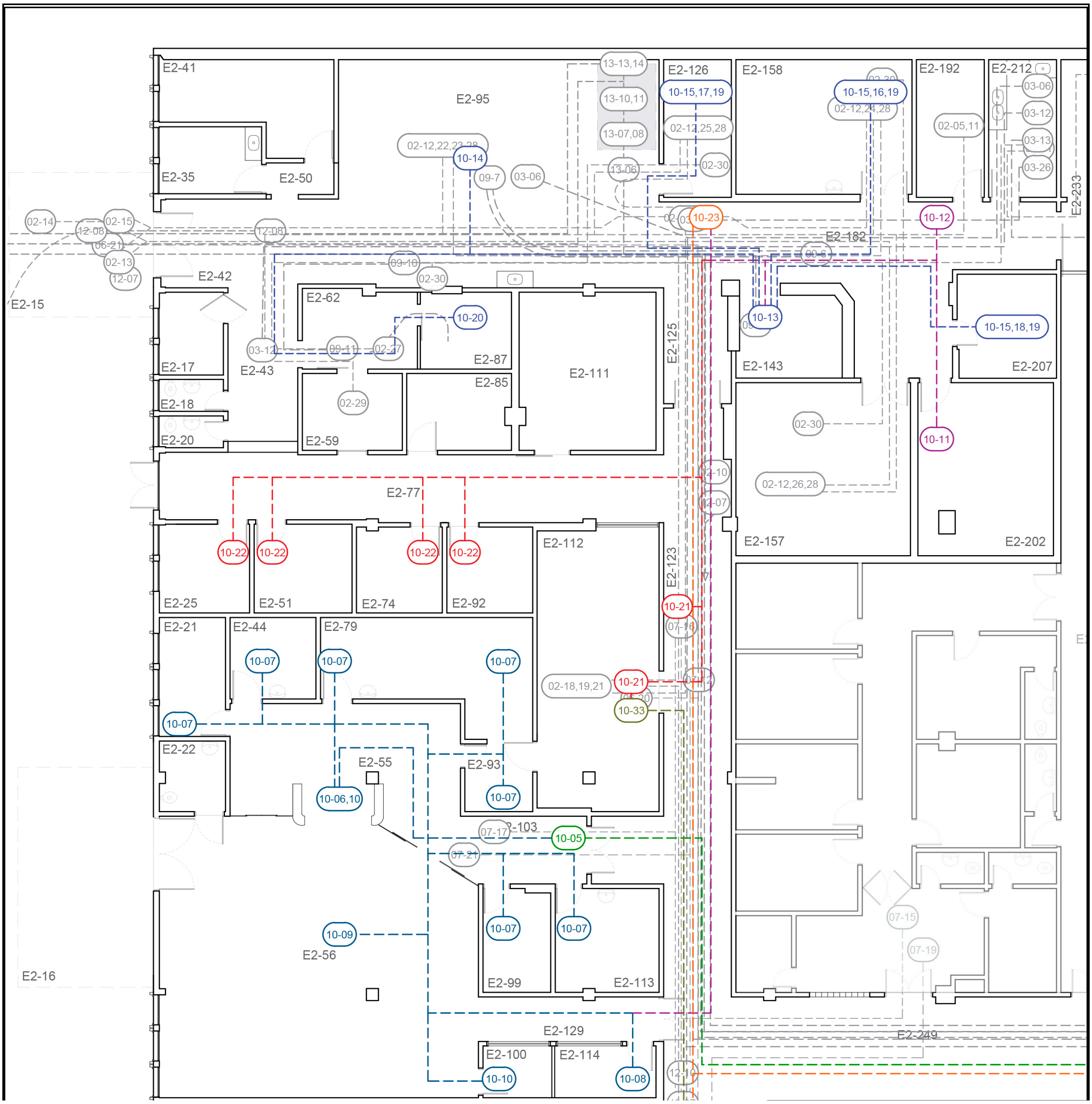
The interview material is protected by the terms of free informed consent and is in the sole possession of the main researcher. The main information that was obtained directly from the interviewees has been compiled in the Supplementary Materials. Although such information reported a specific context, it is possible to relate these data to other cases and identify general layouts and patterns that are characteristic of those that are used by healthcare facilities. The programming used to compute the congruence mapping between the activities and the environment was made available with permission from the Massachusetts Institute of Technology (MIT) [59].

3. Results

The activities, the roles, and the ES environment were related to one another and were allocated on the basis of the information that was obtained through the 13 interviews with users working in different positions at HU (Table 3). The gathered and related data were compiled in lists of activities, environments, roles, and relationships (see S2–S5). The allocations and the pathways of the different professionals' roles were documented on the floorplans.

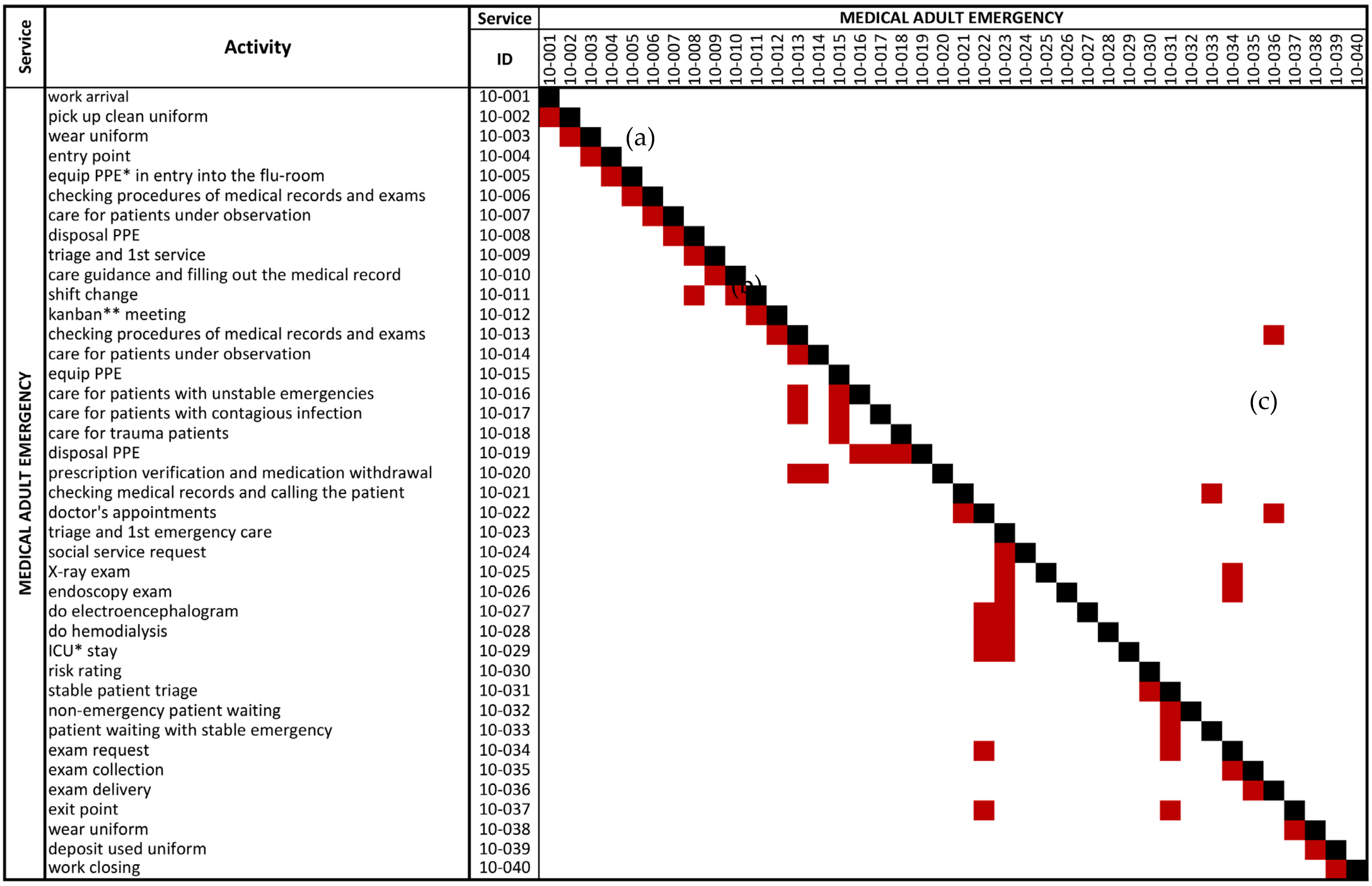
The records covered three hospital floors, as the ES-related activities extended to all of these areas. In the report, we only highlighted the parts that supported the understanding of the discussion. Figure 3 presents a schematic of the two main floors that were involved with the hospital's main sectors.

Figure 4 shows the AED sector in detail. The paths and the activities that were identified in the sector have been crossed out and allocated on this basis. In the research records, the activities of each role were separated in order to facilitate reading. Figure 4 shows the medical activities, in color, overlayed by the paths of the other roles in gray. The overloaded nature of these lines illustrates the complexity of the AED's activity flows. In the research records, the activities of each role were separated in order to facilitate reading.



AED ambulance access	E2-015	medical conference room	E2-041	medication room	E2-062	infirmary room	E2-100	circulation	E2-129
external access	E2-016	access circulation	E2-042	clinic	E2-074	circulation	E2-103	nursing station	E2-143
patients' bathroom	E2-017	circulation	E2-043	circulation	E2-077	plaster room	E2-111	trauma room	E2-157
patients' bathroom	E2-018	clinic	E2-044	medication room	E2-079	orange waiting room	E2-112	circulation	E2-182
patients' bathroom	E2-020	circulation	E2-050	clinic	E2-085	clinic	E2-113	nursing leadership room	E2-192
clinic	E2-021	clinic	E2-051	medication room	E2-087	PPE equip room	E2-114	didactic support room	E2-202
bathroom	E2-022	nursing station	E2-055	PPE removal room	E2-093	circulation	E2-123	dressing room	E2-207
clinic	E2-025	yellow waiting room	E2-056	observation room	E2-095	circulation	E2-125	purge/cleaning supply	E2-212
kitchen	E2-035	supply room	E2-059	clinic	E2-099	isolation room	E2-126	circulation	E2-432

Figure 4. The AED sector plant floor, with an indication of the flow of medical activities, was constructed based on SEF HU USP files. The flow of medical activities is highlighted in color, and the flows of the other roles are indicated in gray. Each color indicates a medical activity sequence. The code with the prefix "E" refers to the listed environments. The codes in balloons refer to the activities. In this case, the number 10 before the hyphen indicates the medical role, and the number after the hyphen indicates the medical activities (activity column in Figure 5).



Legend: identified *i* and *j* relationship; there is no relationship when i and j are the same
Abbreviations: **PPE** - personal protection equipment ; **ICU** - intensive care unit ;
****Kanban** - is a signboard that controls flows and resources in a productive organization, such as transformation, transportation, or other services.

Figure 5. Activities matrix (Ann) in detail, highlighting the medical activities conducted in an adult emergency-care service. This matrix clipping presents 40 activities out of the 325 activities contemplated in the entire matrix (see the full matrix in S7).

All of the relationships that were obtained from the records were annotated using the syntax of the application (Table 4). While the script was running, any inconsistencies in the records were indicated for correction or complementation. After completing the checking of the integrity of the input records, the relationships were calculated as indicated in Figure 2.

3.1. Situation Record Matrices

Among the output data were two DSMs, which were used to organize the relationships of the activities by activities (A_{nn}) and the relationships of the environments by environments (E_{mm}) (see full matrices in S6 and S7). Figure 5 shows the details of the DSM of the activities, with emergency clinical activities listed as reported in an interview. The interpretation of the matrix is as follows: The black cells show the activity point in the list and the red cells indicate the dependence of the activity in the line. In Figure 5a, the initial lines present the sequential activities. Figure 5b presents the triage and the referral activity set, with these activities understood here as parallel activities. Figure 5c presents the cyclical activities, that is, the cases where the completion of an activity is resumed after the completion of other activities that are initiated by it.

The relationship matrix (R_{nm}) defines the affiliation between the activities and the environments, assigning colors to the values that are indicated in Table 1 in order to point out where the final activity takes place in the environment, if it is a middle activity, or if it is a circulation between environments to realize an activity (Figure 6).

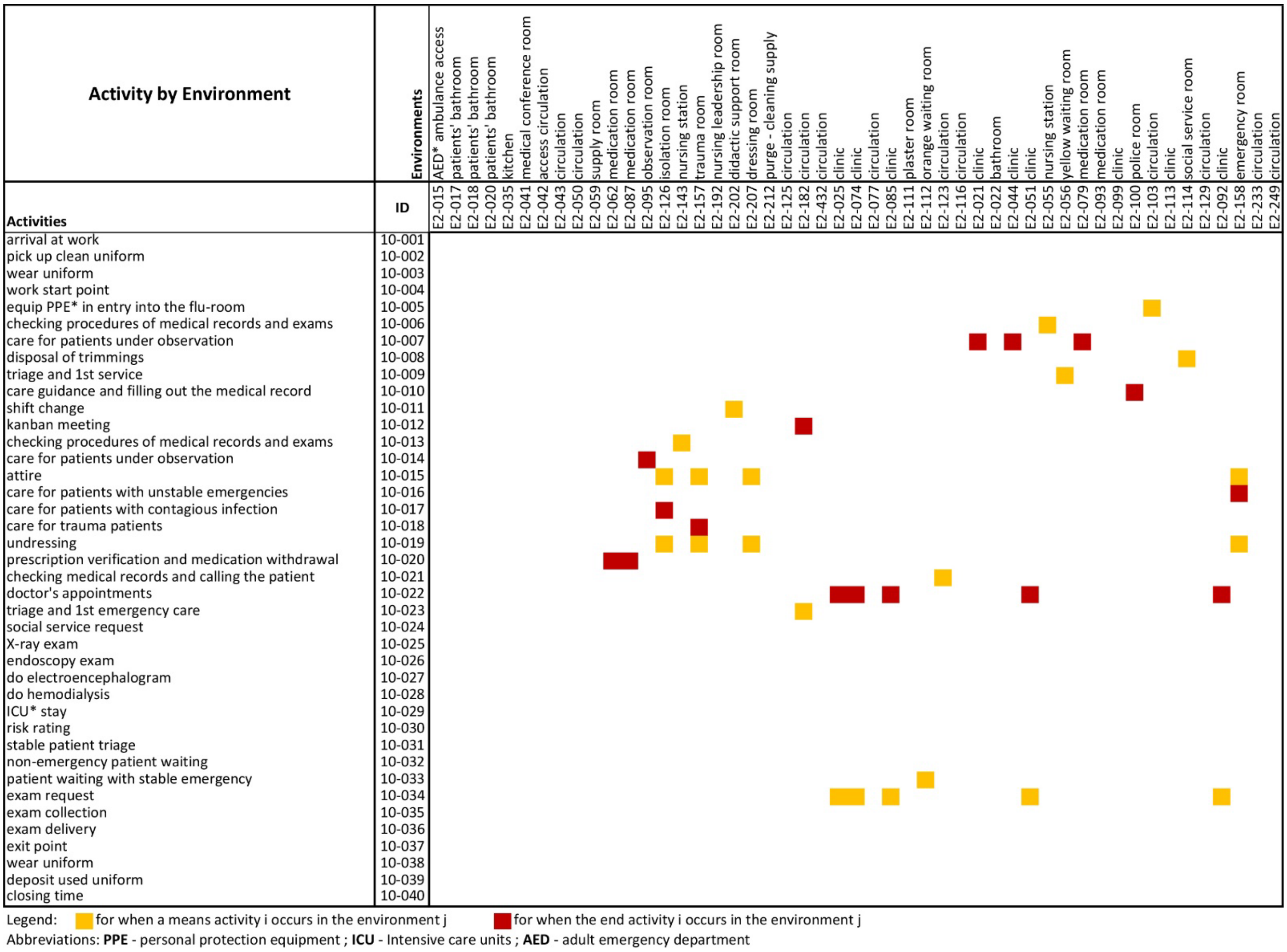


Figure 6. Detailed relationship matrix (R_{mn}) of the medical activities in AED (see full matrix in S8).

Although they allow the visualization of the relationships between the process and the space domains, the E_{mm}, A_{nn}, and R_{nm} matrices are matrices that are used for registering the perceived reality, without calculating potential interactions.

3.2. Congruence Matrices

The congruence matrices present multidomain information by highlighting the unmapped indirect influences through logical debugging.

The environment congruence matrix (eC_{mm}) indicates the relationships of the environments that allocate the same activity or a sequence of dependent activities (Figure 7). When the relationship between the two environments has a dark blue indicator (see color legend in Table 2), it means that the physical relationship is justified by one or more of the activities that pass through these environments to be carried out. When a relationship is depicted in light blue, it means that the designations of these environments can be reallocated and replaced by the activities that interact with the activities in adjacent rooms. The red color indicates that there is potential for reallocation between uses, so it refers to contiguous spaces or spaces that are connected by a circulation process. Indications in red appear in other support activities, in which the environments where the middle activities are carried out are located far from the environment where the end activity takes place. For example, the cleaning activities exhibited a series of red indicators because the storage of materials and the parking of cleaning carts were located far from the emergency department area (matrix in S10).

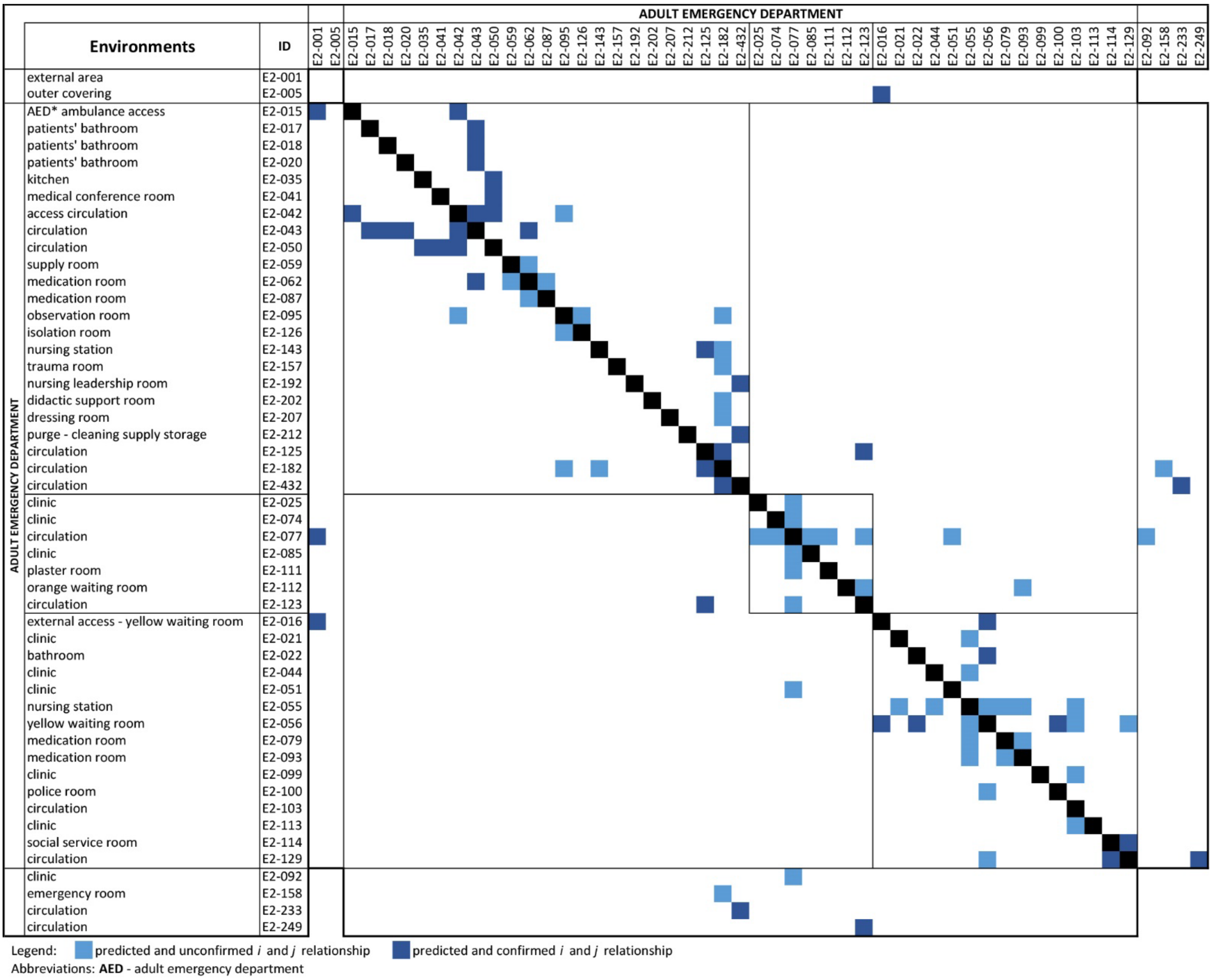


Figure 7. Detailed environment congruence matrix (eCmm), highlighting the relations between AED environments. Rows have been reordered to group department rooms (see the full matrix in S9).

In a context in which, when reallocating the uses of environments, the congruence indices do not fall or improve—that is, the number of predicted and fulfilled relations remains the same or increases, or the number of relations not attended to remains the same or decreases—this means that the reallocation was successful without the need for changes in the building design. In this context, the manager can explore changes in use in the environments in which the need for close environmental relationships were not detected (light blue indications). This can be used to test changes to the existing mapping, simulating alternative allocation scenarios to the existing one. However, if the congruence indices drop when reallocating the uses of the environments, this may mean that there is a need for intervention in the design. In this second context, mapping becomes a PDE tool that supports the decision to start a design and guides the definition of change requirements. Furthermore, the congruence indices can be used as a parameter to support the decision to evaluate and the decision to accept a design proposal.

The activity congruence (aC_{nn}) indicates the interactions of the activities that can share the same environment while they are being performed (Figure 8). This matrix is a complementary instrument that can be used to guide the facility manager in defining the potential reallocations of activities. It presents the relationships between the activities that are not indicated in the activity map (A_{nn}), but which potentially exist due to the crossing of relations, as logically processed by the application.

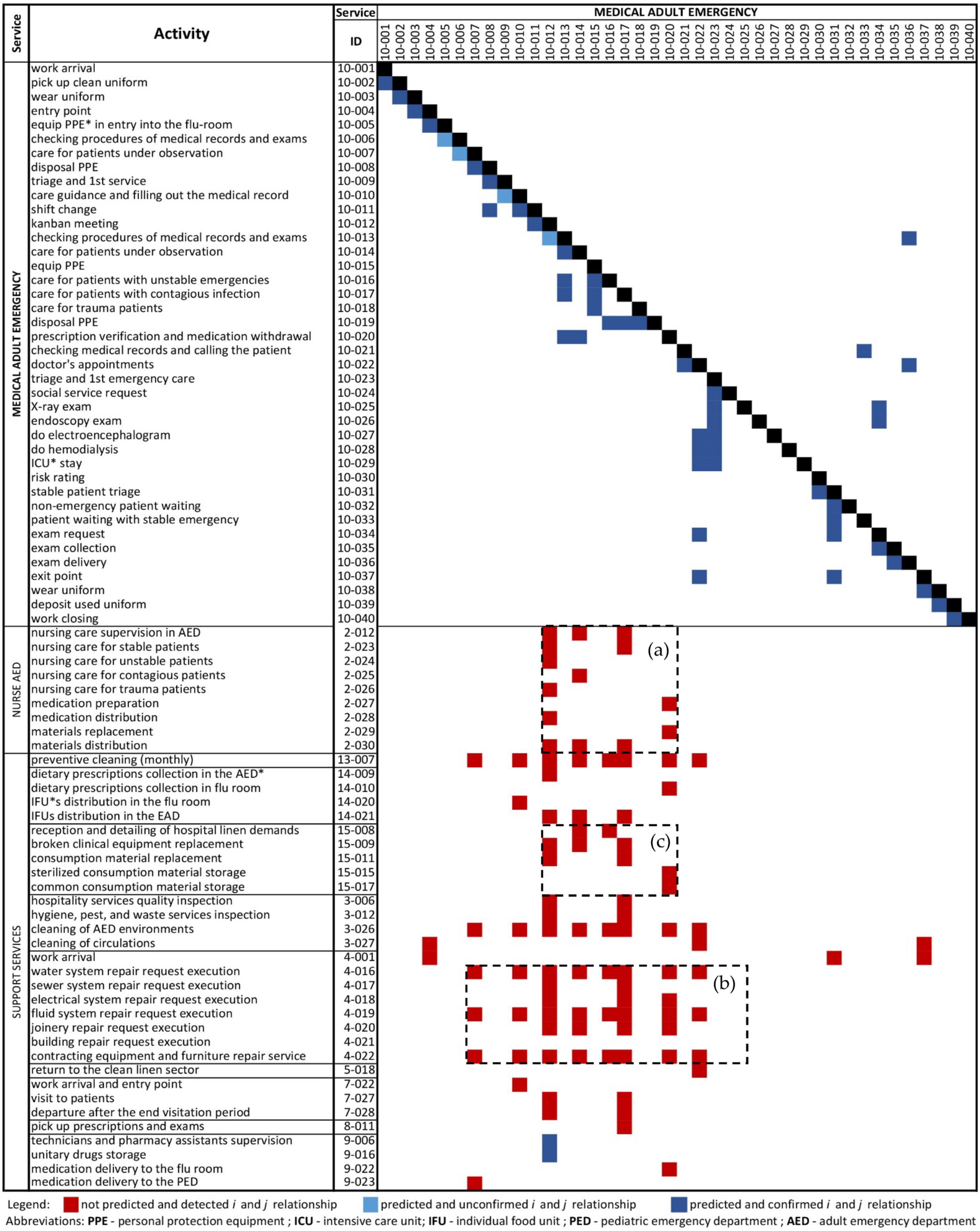


Figure 8. Detailed activity congruence matrix (aC_{nn}), highlighting the relationships between the medical activities in ESs and other activities. Rows have been reordered to show the other activities that are related to the medical activities (see the full matrix in S10).

In the case that has been presented, the unattended potential relationships link the clinical activities to the support activities. These are indications that need to be analyzed and validated. The solution is not necessarily linked to the change in the allocation but it indicates that there are interfaces that have not been considered in the mapping, but which are possible because they occur in a common environment.

The highlighted area in Figure 8a indicates unattended relationships between nursing and medicine. The first column refers to activities that are linked to the Kanban carried out by the entire team. In another case, personal protective equipment (PPE) distributions were not linked to the doctors' attire. Both of these cases deal with unrecorded existing relationships. Once they are detected, it is up to the manager to review the records with this addition and then to run the script. In another example, it was observed that the set of unmet relationships between the ES activities and the maintenance activities (Figure 8b) pointed to the lack of a repair communication procedure.

On a case-by-case basis, the items that are highlighted by red cells can be analyzed in context so that an appropriate decision can be made. Eventually, checking some of these points will require allocation changes. For example, when investigating the reason for the allocation of items that are related to the hospital linen room (Figure 8c), the availability of another place for the storage and replacement of consumables enabled the congruence to be increased (as well as reducing the number of items that had not been attended to).

4. Discussion

The analysis of the organization of the activities in relation to their allocation within the environment [16,27] is a step towards improving healthcare services, especially in emergency departments, where intense work dynamics demand the optimization of resources [12]. The MC-MD is a lightweight computational instrument that proved to be a potential support for managerial decisions and pre-design activities by allowing a systematic evaluation of the allocation of activities in the built environment, even with little input data available. The ability to use such inputs is especially relevant in contexts where architects and construction managers renovate buildings based only on their professional insights [25].

The execution of the instrument demonstrated some of its potential uses for facility managers and designers. It presented a means of mapping the relationships between activities and environments in a complex system such as an emergency department and carried out congruence mapping between these two domains, relating them through a structure of multi-domain matrices [42]. Thus, it made it viable to model change scenarios in a simple and fast way. Without having to master geometric modeling instruments or any other specific instrument in addition to lists [12], it is possible to feed the software with the available data.

Based on this case study, the following application opportunities in different situations were identified:

1. The A_{nn} matrix points out the cyclical activities in the analyzed service, that is, cases in which the execution is repeated without a defined order. In order to reduce travel activity—which does not add value—and thus increase efficiency, the allocation of these activities must be combined and eventually integrated visually. This information is interesting mainly when an environmental arrangement has not yet been defined. When an environmental allocation exists, matrix aC_{nn} allows the same reading to be obtained and adds a congruence indication;
2. In the R_{mn} matrix, it is possible to identify mandatory passages (value one, yellow, in Table 1) in order to test the impact of restricting circulation through determined passageways. For example, when simulating the segregation of the flow of contagious

inpatients or cleaning activities, the manager can verify that the existing environmental arrangement is not adequate, which demonstrates the need for a reformed design of the ED access spaces;

3. The eC_{mm} matrix indicates a congruent relationship between environments, depending on the allocated activities. Thus, it is possible to identify a room for which the allocated activity is not congruent with the others and replace it with an activity that requires an adjacency relationship in order to gain efficiency. For example, one can test the alternative location of a local warehouse for cleaning materials and linen in order to reduce the travel distances for supplies. In the case that has been presented here, a situation of non-congruence was not identified (value one, red, Table 2) because it was a real case. In the case of a design process that has not been executed, the lack of some relationship will be pointed out when an interface is identified between the environments whose activities demand a relationship. This is a particularly interesting resource in regard to design requirements and the validation of new proposals;
4. The aC_{nn} matrix allows the mapping of the relationships between the activities that were not indicated as inputs, but which were mapped with potential relationships. This map can be used to investigate the reasons for pointed non-congruence, whether it is because of lack of input relationships, because the activities cross each other and coexist in the same environment, or because they require an environmental or procedural rearrangement.

In addition to operational applications in facility management and design, the software supports a strategic approach. The quantification of congruence can even be adopted as a quality parameter for the occupation of an environment. In order to define a congruence KPI, it is necessary to debug the performance parameters based on the total number of satisfied and unsatisfied quantifications of relationships [28]. As suggested, the MC-MD serves different purposes, contexts, and scales of use. The mapping of relationship points through simple lists that are used as input records is a flexible evaluation strategy that allows the identification of potential points of conflict and opportunities for improvement without requiring too much data. These realizations are made available using a few computational resources for fast processing, which is understood as a condition for a program to be used in different contexts.

4.1. Conclusions and Future Research Directions

In order to meet the demand for better quality in the delivery of complex services, such as ESs, organizational interventions are needed regarding the flows of activities and the arrangement of the environments that are allocated for these purposes. The results of this study support the identification of current and potential future allocations of activities in existing environments. In this case study, a resource was offered for POEs, as this study's results presented a means of assessing the reality that was experienced by the occupants, based on their coded reports. This allowed the facility manager to prioritize the reallocation of activities when a change was required, providing an opportunity to obtain a complete understanding of the allocation of activities, as well as indicating some points of conflict and opportunities to adjust the allocation of activities in order to improve the environmental conditions and support the services that are offered.

Considering the demand for improvements in health infrastructure that is dedicated to emergency care, mapping is also an appropriate step in initial reform studies and fornew designs. This perspective is an extrapolation of the current application to analyze congruence in PDEs. The application of the method/software in an initial design study is proposed as the next stage of research development. In this case, in addition to understanding how to interpret congruence maps, an apparatus of strong evidence is needed in order to formulate alternative environmental arrangements and flows, the congruence mapping of which will be simulated.

With the successful simulation of congruence in the design process, it is expected that the congruence mapping of the flow of allocated activities will represent a design support framework in association with other EBD resources. Finally, other applications are needed in order to improve the software and the map analysis method.

4.2. Research Limitations

The main limitation of this study is that it was based on a single case. However, the case was not intended to represent a generalizable sample, but rather to test the functionality of the proposed instrument based on existing theory. If usability is confirmed with the application of the tool in multiple cases, the shared data can be compared in a meaningful sample, which would allow some generalization. This possibility goes beyond the limits of the present research and would only be possible through larger multidisciplinary academic collaboration.

The case was analyzed in detail with regard to the floorplans, the activities, the flows, and the environmental arrangement. Other organizational domains, such as the availability of material resources and the culture and policies that influenced the emergency-care services provided, were not directly considered. They were instead isolated as uncontrolled variables. As this study was in a specific context, the analysis of this case can be extended to other ESs only as an inductive reference. The strength of the instrument that has been presented here is that it offers the means to map many contexts, and, through the accumulation of comparable data, strong evidence could be obtained that would allow generalizations to be drawn. We encourage the congruence mapping and reporting of other cases.

4.3. Patents

The current discussion addresses the development of the basic functions of the program, with open-source software. For the validation of this function, software with a friendly interface will be elaborated further in order to provide better usability in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13031599/s1. S1: Interview script model; S2: Activity list; S3: Environment list; S4: Function list; S5: Relationships; S6: Environments matrix (E_{mm}); S7: Activities matrix (A_{nn}); S8: Relationship matrix (R_{mn}); S9: Environment congruence matrix (eC_{mm}); S10: Activity congruence matrix (eC_{mm}).

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the research ethics committee of the University Hospital of the University of São Paulo (CEP/HU/USP) (protocol code CAAE: 44679021.0.0000.0076, approved on 26/03/2021).

Informed Consent Statement: Written informed consent has been obtained from all subjects involved in this study.

Data Availability Statement: The programming that was used for mapping the multidomain congruence is available from the author's and collaborator's accounts, through the links: [supplement], or the links: "https://github.com/LC-MP/PosDoc_MScMD_0.0", "https://github.com/Jean-Amaro/Xablau/tree/main/OrganizationalAnalysisApplication".

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