Evolution Process of Scientific Space: Spatial Analysis of Three Groups of Laboratories in History (16th–20th Century)

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Abstract: Different disciplines need specialized spaces to ensure the smooth conduct of research, and the laboratory plays an important role as the physical carrier of knowledge production today. Reviewing history, it is found that the image of the laboratory and the organization of internal space have undergone great changes, which reflects people’s cognition of scientific practice in different periods. This study uses space syntax tools to analyze relationships between scientific research activities and spatial forms over time, preliminarily discussing laboratories’ spatial characteristics in different periods and the corresponding research modes. It is found that scientific research has undergone several phases, and the scientific paradigm deeply influences the spatial logic of scientific research buildings. The scientific research space in different periods presents unique syntactic results and topological structures, suggesting the trend of specialized research from closed to open and decentralization to centralization.

Keywords: spatial syntax; laboratory space; historical evolution; scientific research activities

1. Introduction

The historian of science, Owen Hannaway, once mentioned that science was no longer simply a kind of knowledge; it increasingly became a form of activity. The laboratory is a place specially set aside for such activity [1]. From the secret underground experimental space of Tycho Brahe to the modern large-scale science facility, the internal space and external image of today’s laboratories have undergone fundamental changes over the last few centuries with the development of science and innovation in construction technology. The definition of a laboratory has also been revised from the original “chemist’s work-house” to “the building set apart for conducting practical investigations in natural science” [2].

From the sociological point of view, a laboratory is a place for knowledge production. The typical scientific activity in the laboratory is connecting the experimental materials to the instruments, generating records through a series of standardized operations, and then putting forward scientific propositions according to these records and modifying them repeatedly until they become facts [3].

Peter Morris believes that changes in function affect the form of the laboratory, and the development of a new field has often produced significant alterations in laboratory design [4]. The early scientific activities were mainly desktop experiments organized spontaneously by the elite based on their interests, usually in the study, kitchen, and other enclosed places. The increased complexity of scientific research and the interpenetration of disciplines have led to collaborative progress between scientific organizations, prompting the need for greater inclusivity and flexibility in the laboratory space.

In contrast to the past, the scope of scientific research activity is no longer confined to limited benches and rooms, and the emergence of continuous open areas encourages more creative activities and academic exchange. As a forward-looking institution, the evolution of the laboratory is closely related to the development of science and technology. In retrospect, the spatial configurations of laboratories in different historical periods make...
a statement about the status of academic teaching and research and researchers’ attitude toward using space.

This study selects three groups of typical laboratories to provide new readings on scientific research space, revealing the topological type and genotype of the laboratory space in different periods, which is an abstract relational model that describes space configurations [5]. Given the complexity of laboratory layouts in various disciplines, this study is limited to the basic spatial configuration of experimental space and other functional spaces rather than a specific analysis of laboratory layouts by disciplinary classification. In this study, qualitative and quantitative types are determined by using justified graphs and their outcomes in the form of syntactic measures.

2. Literature Review

In the field of laboratory culture before the 20th century, few studies focused on the sites and space of experiments. It has been argued in the history and philosophy of science scholarship that the laboratory itself is merely a nodal point with no volume, materiality, or spatial identity [6]. Scholars before the 1960s tended to study etchings and paintings of early modern laboratories as credible sources to gather information about the equipment and working methods employed in historical laboratories but rarely included analyses of space or architectural structures [7–9]. Compared with laboratory design, the historical research on laboratory space from the architectural perspective accounts for a relatively small proportion, usually appearing as a brief historical review at the beginning of some design books.

From the perspective of disciplinary development, as early as 1975, scholars evaluated the global geographical distribution, personnel management, and knowledge production of physical research institutions at the beginning of the 20th century [10]. After the British scholar Maurice Crosland’s study of early laboratory construction in the 16th–18th centuries [11], Morris systematically traced the evolution of laboratory facilities in chemistry from the Middle Ages to modern times [4]. Similar studies have been carried out in pharmacy and anatomy [12,13]. In other aspects, Ursula Klein traced the history of technoscience, mapping the relationship between today’s cutting-edge disciplines and the development of the useful and technological sciences in Prussia from 1750 to 1850 [14]. Aileen Fyfe placed sciences in a broader cultural marketplace and discussed the evolution and presentation of “popular science” in Victorian Britain [15].

In addition, scholars discussed the spatial characteristics of scientific activities since the Renaissance from the perspective of engineering, sociology, and design [16]. The above research paid more attention to the material and cultural connotations reflected behind the experimental activities, ignoring the spatial characteristics of the laboratory. Furthermore, the historical development of laboratory buildings is not clear. Nancy B. Solomon once regarded laboratories established after World War II as modern laboratories different from the past based on flexibility. Peter Galison argued that with the improvement of industrialization at the end of the 19th century, flexibility had begun to take shape [17]. Andrew Cunningham believed that the 19th century was an important turning point in the history of science [18].

Depending on the historical shifts of scientific centers, the degree of institutionalization, and different participants, here we divide the evolution process of scientific space into four phases: Individual exploration, professional research, centralized research, and integrated interdisciplinary research (Figure 1). This study focuses on the first three phases. Several cases are selected for topological analysis to reveal the spatial logic of laboratories in different periods and the relationship between the public space and experimental units.
Figure 1. Evolution process of scientific space (source: The authors).
3. Method and Selection of Cases

According to space-syntax comprehension, space forms and organizations exist to coordinate various social activities, and the generation logic of space is consistent with human behavior. As a set of analytical measures for representing and quantifying spatial configuration, space syntax focuses on the potential relationship between form and function, space and users, by focusing on the specific connection between spaces.

This study establishes the topological relationship to obtain visual representation and values of each functional space using DepthmapX and JASS software. DepthmapX enables the depiction of buildings to generate a map of spatial elements, link them through relationships (visibility, intersection, or adjacency), and analyze the resultant network [19]. JASS is intended for convex space analysis to draw networks and convert graphs into justified graphs by transforming spaces and their connections into points and lines, which will be presented in the deep-branched tree form, shallow-ring bushy form, etc. [20–22].

Taking the Chemical House as an example, Figure 2 shows the transformation process from a plan to a justified graph. Firstly, a convex break-up map is created. The connections between spaces are extracted to form a set of topological networks, with each node corresponding to a room in reality. In turn, the spatial properties of all nodes are grouped according to functions such as public (P), experimental (L), courtyard (CRT), and service (Se). The convex map is then represented as a justified graph, and the exterior (public space) is taken as its root to connect from the bottom up. Here we obtain the spatial topology of one case and repeat the process to obtain the diagram of the remaining cases.

The following parameters are considered in this study:

Integration (HH) is the most widely used syntactic value, calculating how close the origin space is to all other spaces as the measure of relative asymmetry (RA) [23,24].

The base difference factor (BDF) is used to investigate the difference between various functional spaces. The value changes between 0 and 1. The closer to 0, the more differentiated and structured the spaces; the closer to 1, the more homogenized the spaces, and no configurational differences exist between them [20].

In addition, it is also important to derive certain in-depth syntactic measures related to the topological network, such as the distributedness index (ID) and space link ratio (SLR). The distributedness index (ID) is based on the four topological spaces (a, b, c and d), with ‘a’ and ‘b’ space types emphasizing tree-like configurational properties while ‘c’ and ‘d’ space types are conducive to ringiness [25]. Distributedness can be calculated by the formula \((a + b)/(c + d) = \text{distributedness}\), reflecting the available options for accessing all spaces in the system [20]. The space link ratio (SLR) is used to evaluate the distribution of the spatial layout, indicating the flexibility of movement in the system. The parameter expressions involved are as follows:

\[
\text{MD} = \frac{\text{TD}}{k - 1} \quad (1)
\]
\[
\text{RA} = 2\frac{\text{MD} - 1}{k - 2} \quad (2)
\]
\[
D_k = \frac{2(k\log_2\left(\frac{k+2}{k}\right)+1)}{(k-1)(k-2)} \quad (3)
\]
\[
\text{RRA} = \frac{\text{RA}}{D_k} \quad (4)
\]
\[
\text{Integration}(\text{HH}) = \frac{1}{\text{RRA}} \quad (5)
\]
\[ H = -\sum \left[ a_i \ln\left(\frac{a_i}{t}\right) \right] + \left[ b_i \ln\left(\frac{b_i}{t}\right) \right] + \left[ c_i \ln\left(\frac{c_i}{t}\right) \right] \quad (6) \]

\[ H^*(BDF) = \frac{H - \ln 2}{\ln 3 - \ln 2} \quad (7) \]

\[ \text{SLR} = \frac{L + 1}{k} \quad (8) \]

The meanings of some parameters involved in the formula are as follows:

- TD: Total Depth for actual node.
- k: Number of nodes.
- a: Max RA.
- b: Mean RA.
- c: Min RA.
- t: a + b + c.
- L: Number of links.

Using these parameters, this study aims to explore the evolution process of the scientific research space and understand the potential organization and cultural pattern of laboratory layouts in different periods. Through the case collection and study, we selected three representative groups of cases for analysis, designed in the late 16th century, the 19th century, and the mid-20th century. Information about the three groups of cases is shown below (Figure 2). The topological structure of each laboratory spatial configuration is represented by convex maps and justified graphs.

Given that syntactical results are directly affected by spatial delineations [26], the following decisions have been made in this study. Firstly, the external space is included in the topological structure as the original space (root) of the system to present the spatial organization, but not in the analysis of internal spatial differentiation. Secondly, the main floor is only considered because it contains all the essential functions and is available in the literature [27]. Finally, three types of space are abstracted from cases for differentiation analysis: Spaces for experiments, transition spaces (corridors and public spaces), and service spaces (vertical transportation, toilets, storage rooms, and equipment rooms).

The following paragraphs are intended to highlight the spatial features that exist within cases. The spatial pattern is considered according to the syntactic data and the differentiation degree between the integration values of functions (Tables 1–6). Table 1 shows the global integration and the base difference factor (BDF) for a horizontal comparison between cases. Table 2 shows the integration and the base difference factor (BDF) of the three types of spaces used for the differentiation analysis of each case, aiming to describe the difference in integration between functional spaces of each system and the degree of spatial differentiation within the same function. Table 3 shows the proportion of four topological spaces (a, b, c, and d), the resulting distributedness index (ID), and the SLR of each system for discussion on the topological type.

Furthermore, Tables 4–6 show the order of integration of the main functions and the red dotted line represents the average value. The information can be obtained, such as which rooms in the system have the highest degree of integration and what level (higher or lower than the average value) the integration of the experimental space may be in the system.
Figure 2. Background information of cases: Plans, convex maps, and spatial topologies (source: The authors).
Table 1. Syntactic Data of Cases (Integration (HH), RA, and BDF).

| Sample | Integration (HH) | Relative Asymmetry (RA) | BDF (H*) |
|--------|------------------|-------------------------|----------|
|        | Min   | Mean  | Max   | Min   | Mean  | Max   |         |
| T1-1   | 0.671 | 1.034 | 2.312 | 0.115 | 0.291 | 0.397 | 0.744   |
| T1-2   | 0.604 | 0.972 | 1.961 | 0.132 | 0.296 | 0.429 | 0.761   |
| T1-3   | 0.753 | 1.323 | 2.929 | 0.086 | 0.217 | 0.333 | 0.696   |
| T2-1   | 0.634 | 1.208 | 2.304 | 0.036 | 0.074 | 0.130 | 0.703   |
| T2-2   | 0.601 | 0.945 | 1.700 | 0.108 | 0.210 | 0.307 | 0.805   |
| T2-3   | 0.647 | 1.080 | 1.996 | 0.074 | 0.146 | 0.229 | 0.772   |
| T3-1   | 0.897 | 1.903 | 3.638 | 0.020 | 0.044 | 0.081 | 0.657   |
| T3-2   | 1.253 | 2.188 | 7.291 | 0.011 | 0.038 | 0.065 | 0.547   |
| T3-3   | 0.466 | 0.876 | 1.454 | 0.058 | 0.101 | 0.182 | 0.751   |

Table 2. Differentiation Degree Between the Integration Values of Different Functions.

| Sample | Mean Integration (HH) | Transition Spaces | Service Spaces | BDF (H*) | Transition Spaces | Service Spaces |
|--------|-----------------------|-------------------|----------------|----------|-------------------|----------------|
|        | Laboratory Spaces     |                   |                | Laboratory Spaces |                   |                |
| T1-1   | 0.771                 | 1.599             | 0.832          | —        | 0.893             | —              |
| T1-2   | 0.681                 | 1.119             | —              | 0.986    | 0.924             | —              |
| T1-3   | 1.347                 | 2.929             | 1.201          | 0.763    | 0.973             | 0.998          |
| T2-1   | 1.101                 | 1.571             | 1.516          | 0.864    | 0.914             | 0.972          |
| T2-2   | 0.996                 | 1.304             | 0.707          | 0.976    | 0.914             | 0.972          |
| T2-3   | 0.997                 | 1.421             | 1.036          | 0.965    | 0.922             | 0.993          |
| T3-1   | 1.541                 | 2.377             | 1.766          | 0.943    | 0.887             | 0.877          |
| T3-2   | 2.359                 | 3.833             | 2.257          | 0.966    | 0.852             | 0.967          |
| T3-3   | 0.851                 | 1.093             | 0.788          | 0.987    | 0.785             | 0.848          |

"—" Some difference factors are not calculated because there are only two types of interior space in the system or the absence of this type of space.

Table 3. Topological Types and Calculated Values of ID and SLR.

| Sample | Node Count | Space a | Space b | Space c | Space d | Distributedness Index (ID) | SLR |
|--------|------------|---------|---------|---------|---------|---------------------------|-----|
| T1-1   | 14         | 9       | 5       | 0       | 0       | —                         | 1.000|
| T1-2   | 15         | 6       | 4       | 5       | 0       | 2                         | 1.070|
| T1-3   | 16         | 7       | 1       | 4       | 4       | 1                         | 1.250|
| T2-1   | 103        | 58      | 20      | 17      | 8       | 3.12                      | 1.160|
| T2-2   | 29         | 10      | 2       | 13      | 4       | 0.706                     | 1.210|
| T2-3   | 42         | 9       | 5       | 15      | 13      | 0.5                       | 1.310|
| T3-1   | 124        | 83      | 7       | 20      | 14      | 2.647                     | 1.150|
| T3-2   | 105        | 98      | 7       | 0       | 0       | —                         | 1.000|
| T3-3   | 99         | 19      | 8       | 19      | 53      | 0.375                     | 1.580|

"—" Some values are not calculated because of the absence of this type of space.

Table 4. Order of Integration Values of Main Functions (T1).

T1: Uraniborg—11 function space

P: 2.23 > C3: 1.60 > C2: 1.39 > C1: 1.10 > 1.034 > B2: 0.83 = V: 0.83 = K: 0.83 > B1: 0.77 = L: 0.77 = Li: 0.77 > E: 0.67

T1-2: Stellaeborg—12 function space

P: 1.96 > C1: 1.57 > C5: 1.31 > C4: 1.07 > C3: 1.02 > 0.972 > C2: 0.91 > E: 0.84 > L2: 0.78 > L3: 0.76 = B: 0.76 > L2: 0.65 > L1: 0.60

T3-1: The Chemical House—13 function space

P: 2.93 > L1: 2.40 > L2: 1.88 > 1.323 > Se1: 1.26 = V: 1.26 = L6: 1.26 > L3: 1.15 = Se2: 1.15 > L4: 1.05 > L7: 0.94 > CRT: 0.85 > L5: 0.75 = St: 0.75

Key: E-Entrance; L-Laboratory; P-Public space; V-Vertical transportation; CRT-Courtyard; B-Bedroom; K-Kitchen; Li-Library; St-Store room; Se-Service; C-Corridor

The bold underlined value is the mean value of integration in the system. More information about the rooms (location and connection relationship) can be obtained from Figure 2.
Table 5. Order of Integration Values of Main Functions (T2).

| T2-1: Fraunhofer Institutes—19 function space |
|---|
| C2: 2.30 > C3: 2.08 > C1: 1.99 > CRT: 1.96 > V2: 1.95 > C4: 1.54 > P2: 1.49 = S: 1.49 > V3: 1.49 > P4: 1.41 > P3: 1.39 = L1: 1.39 = V4: 1.39 = V5: 1.39 > P1: 1.36 = D: 1.36 > V1: 1.36 > **1.208** > L2: 0.9 > W: 0.81 |

| T2-2: Physiological Institute, University of Leipzig—18 function space |
|---|
| C2: 1.70 > C3: 1.66 > C3': 1.37 > C1: 1.24 > L4: 1.11 > L3: 1.07 > L2: 1.06 > L6: 1.04 > L7: 1.03 = A1: 1.03 > C4: 0.97 > **0.945** > E: 0.89 > C1': 0.88 > L1: 0.85 > L5: 0.79 > A3: 0.76 > P: 0.75 > A2: 0.60 |

| T2-3: Physiological Institute, University of Budapest—24 function space |
|---|
| C1: 2.00 > C2: 1.67 > C5: 1.62 > P1: 1.35 = CRT2: 1.35 > A2: 1.29 > L2: 1.24 = C3: 1.24 > L3: 1.23 > E: 1.23 > L1: 1.22 > P2: 1.17 > A1: 1.12 > C4: 1.11 > L1: 1.09 > **1.080** > L7: 0.97 > R: 0.92 > L6: 0.87 > L10: 0.85 > L4: 0.82 > L5: 0.817 > CRT3: 0.81 > CRT1: 0.65 |

Key: E-Entrance; L-Laboratory; P-Public space; V-Vertical transportation; CRT-Courtyard; Li-Library; Se-Service; C-Corridor; A-Auditorium; R-Research space

The bold underlined value is the mean value of integration in the system. More information about the rooms (location and connection relationship) can be obtained from Figure 2.

Table 6. Order of Integration Values of Main Functions (T3).

| T3-1: Northwestern University Technological Institute—33 function space |
|---|
| C4: 3.63 > C2: 3.08 > C1: 3.01 > C3: 2.55 > C6: 2.25 > C8: 2.17 > C9: 2.15 > A4: 2.02 > O4: 2.00 > C: 1.97 > A1: 1.96 > **1.903** > L2: 1.85 > O2: 1.82 = V2: 1.82 > A2: 1.80 = O1: 1.80 > V1: 1.80 = E1: 1.80 > C5: 1.68 > C7: 1.67 > A3: 1.64 > L3: 1.64 > O3: 1.62 > L6: 1.51 > O6: 1.49 > L4: 1.46 = L8: 1.46 = E3: 1.46 > L5: 1.23 = L7: 1.23 > L1: 1.22 = O5: 1.22 = E2: 1.22 |

| T3-2: ESSO Research Center—18 function space |
|---|
| C2: 7.29 > C3: 3.34 > C1: 3.15 > C5: 3.1 = C6: 3.1 > C4: 3.02 > L2: 2.68 = O2: 2.68 > **2.188** > L1: 1.87 = O1: 1.87 > O5: 1.81 = E2: 1.81 > L3: 1.79 = O3: 1.79 > O6: 1.79 = E3: 1.79 > E1: 1.78 > O4: 1.76 |

| T3-3: Koppers Company Research Center—22 function space |
|---|
| C1: 1.45 > C2: 1.38 > C1': 1.19 > C0: 1.141 > C2': 1.138 > O1: 1.08 > O2: 1.03 > C3: 1.01 > L1: 0.93 = O1': 0.93 > O: 0.9 > L2: 0.898 = O2': 0.898 > **0.876** > C3': 0.87 > O3: 0.81 > E: 0.8 > L3: 0.72 = O3': 0.72 > A: 0.67 > P2: 0.6 > P1: 0.59 > P3: 0.52 |

Key: E-Entrance; L-Laboratory; P-Public space; V-Vertical transportation; O-Office; Se-Service; C-Corridor; A-Auditorium

The bold underlined value is the mean value of integration in the system. More information about the rooms (location and connection relationship) can be obtained from Figure 2.

4. Historical Frameworks of Samples

4.1. Individual Exploration in Private Sites

The development of early scientific experimentation was closely related to alchemy. In the 6th century BC, there were discussions about the origin of things in Greece. Until the Middle Ages, famous scientists and nobles including Leibniz and Newton had studied alchemy [28]. Existing research in the history of science tends to regard the workplace of alchemists in the 16th century as the prototype of the early laboratory, which usually contained furnaces and distillation equipment. Scientific research in this period was predominantly individual exploration with decentralized approaches and available places to conduct experiments, even in the kitchen and living room [29]. Some experimental philosophers moved away from the secular space and placed knowledge in a restricted area at home [30].

The early laboratories with detailed drawings are Uranienborg and Stjerneborg (T1-1 and T1-2) on the island of Ven, described by the Danish astronomer Tycho Brahe in a book about astronomical instruments published in 1598. Influenced by popular astrology thoughts, the layout of the two astronomical observation facilities is symmetrical with the geometric center. In the case of Uranienborg, for example, the upper space was mainly used for living, with a few rooms used to store large instruments for astronomical observation.
The underground area includes the bedroom, kitchen, and laboratory space transformed from the dining room for alchemy activities [31].

Inspired by Tycho’s laboratory, the German chemist Andreas Libavius described the Chemical House (T1-3) in detail, which is introduced as an ideal laboratory for researchers in his commentaries to his textbook of chemistry in 1606. In contrast to what he saw as the aristocratic seclusion of Uraniborg, Libavius viewed his Chemical House as being incorporated into the town and, thus, the public realm [32]. The plan unfolds around the central hall, and the privacy of the overall layout gradually increases from east to west. The main entrance of the building is on the east side, surrounded by a semicircular garden with galleries. The central part is composed of a central hall and experimental spaces, including the coagulatorium and crystallization room, steam baths room, water baths room, and service spaces (toilets and storage rooms) [4]. In addition to experimental technicians, some professionals were allowed to visit. On the west side is a set of private laboratory spaces leading to the study and residential area on the second floor through the staircase [33,34].

Taking the entrance as the original space, a group of topological structures is obtained from the above cases, as shown in Figure 2 (T1). T1-1 and T1-2 are deep-branched tree forms in which ‘a’ and ‘b’ space types occupy a large proportion of the system, showing some local symmetry. In addition to experimental spaces, the two cases also mixed with large living areas. The distinction between functions is obscure, and the spatial logic is strongly centripetal, with the rooms arranged around the central space showing traces of residential accommodation. In the justified graph of T1-1, the laboratory room, bedrooms, and kitchen are in the deepest part of the building (topological depth is 5) side by side, and there is no connection between them. This structure is characterized by strong control of internal and external movement with limited movement options.

Moreover, due to the limited scale, the internal function configuration of T1-1 and T1-2 is relatively simple. The public space (P) at the core is the only control point in the system with the highest integration. The integration of the experimental space is close to the bedrooms and kitchen, with a difference of 0.1 or less, which is very weak in this case.

In contrast, T1-3 has several loops, providing occupants with more route choices. Although the ‘a’ type occupies a large proportion of space in the system, the ID values show that the case has a strong distribution. Several experimental rooms are arranged around L2 and multiple loops are formed according to the practical requirements. In addition to the central hall (P), L2 is another control point in the system, which has a high degree of integration and provides asymmetry. In addition, the BDF value of the experimental space in T1-3 is also the lowest of all the cases, which indicates a strong differentiation within the laboratory space. Through a series of rooms from east to west, the function gradually transits from the central hall near the entrance to the private space with low spatial integration, creating a privacy gradient in space configuration.

It is argued that there was a subdivision of scientific research in this period that the ordinary could not perceive: Trying, showing, and discoursing. Trying was an activity that occurred within relatively private spaces, whereas showing and discoursing were events in public spaces [35], distinguishing public knowledge from personal knowledge and general research from specialized research. The content of the research largely depended on the cognitive activities, intellectual interests, and personal preferences of the individual, in contrast to modern scientific research. The syntactic results of the above cases also confirm this to some extent. Functional differentiation within the experimental space shows apparent differences in integration and accessibility. Users consciously establish a privacy gradient to distinguish the research content that can be visited and displayed from private research activities in terms of spatial configuration, which meets the needs of the experimental process and reflects their will.
4.2. Centralized Organization Principles in Laboratories

In the early 19th century, laboratories increasingly became genuine research sites in chemistry, physics, and biology. The scientific practice gradually shifted from individual exploration for interests to cooperation research, closely integrated with industrial production. During this period, the laboratory as the production site of scientific knowledge was separated from the home. Private laboratories and government-led research institutions increasingly emerged, and scientific activities were organized and rapidly developed, especially in Germany.

In 1806, the entrepreneur Joseph Utzschneider gathered several experts to establish the Fraunhofer Institutes (T2-1) in the Benedictine Monastery, purchased from the government 5 km south of Munich. The cloister is the core of the building, which connects different spaces and forms a closed loop of daily life. Its spatial organization is reflected in a stable horizontal continuity, enclosing the central yard on three sides, with the dormitories on the north side (D), the research space on the south side (L), and the library and instrument storage space in the seminary on the west side (S).

The spatial organization of the three/four-sided yard enclosed by buildings frequently also appeared in the layout of the laboratories during this period, which corresponded to the collaboration for research and resulted in a batch of classic laboratories, such as the Leipzig Physiological Institute (T2-2) and the Physiological Institute in Budapest (T2-3). T2-2 is a three-sided layout connected by corridors, with an auditorium in the center toward the courtyard. A small lecture hall and auxiliary rooms are built on the north side as required for teaching. T2-3 is a four-sided layout. The central space is divided into three small courtyards by a lecture hall (A1) and a corridor (C4). The rooms for experiments are placed on the north and south sides. The entrance (E) of the building on the east side is directly connected to the corridor (C1).

The above cases reflect the centralized organization principle behind the enclosed layout with the following characteristics. Firstly, due to the growing demand for experimental spaces, the number of rooms increased and the space topology changed from the deep-branched tree form to the shallow-ring bushy form, which is reflected in the justified graph as several clusters of points that expand upwards at the bottom (near the entrance). Furthermore, the average integration of the experimental spaces is higher than in the past. Secondly, the cases in this period show a strong distribution feature with multiple control points in each case, especially in T2-2 and T2-3. The proportion of ‘c’ and ‘d’ types of spaces in the system increases significantly, which is reflected in the local formation of several small loops. The large number of ‘a’ type spaces in T2-1, unrelated to the experimental function, greatly impacts the ID values. Finally, compared with the past, the function of the public space is further divided into the lobby (distribution space), the lecture hall (exhibition space), and the conference room (discussion space). In some cases, the lecture hall occupies the courtyard space, visually becoming the core of the whole building. Its integration degree is slightly higher than the average, indicating that the efficiency of such space is not high in topology.

4.3. Modular Laboratory under Industrial Structure System

In the second half of the 19th century, industrial modes of production were widely spread in architectural culture, and efficiency became the focal point of architectural technology. Industrial buildings started to use massive standardized components, which were applied to the construction of large laboratories to meet the need for more extensive open areas and flexible space, in contrast to some prewar laboratories built with thick, immovable walls [36]. Moreover, science had gradually become a mainstream profession open to all sectors of society, and collaboration between scientists from different fields was required to carry out more complex research. Given the demand to effectively cope with the structural changes of space due to discipline reform and staff changes, the module was applied to the design of laboratories. Repetitive units were used to generate the overall plan of the building and adapt to different functional requirements and future expansion. Hundreds
of laboratory buildings designed by module were built in the fields of communication, nuclear physics, aerospace, and industry around World War II.

Among the three selected cases, the Northwestern University Technical Institute (T3-1), built in the 1940s, is a typical multi-disciplinary research building, with different academic departments placed in six wings of the building. Each department is equipped with professional laboratories and independent research spaces connected to the public space in the center. The ESSO Research Center (T3-2) and the Koppers Company Research Center (T3-3) were designed by the same architects. T3-2 is composed of three T-shaped modules linked in sequence, with experimental spaces to the north and offices to the south. Each module has independent vertical transportation, service rooms, and an entrance. The layout of T3-3 is loosely arranged, with corridors linking five separate functional areas, including a public reception area, an office wing, and three wings of the laboratory.

The above cases show different characteristics in spatial organization compared with the past. Firstly, the collectivization of science led to the centralization of personnel and a strong relationship between researchers and the organization, which is implicit in the grid extended by standard modules and resulting in more efficient use of laboratory spaces. This spatial configuration tends to form its communities via corridors or other public spaces as the core of each department, maintaining a relatively independent state to focus on its scientific research work.

Secondly, the modular system brings laboratory space flexibility and weakens the differences between laboratories caused by the specific connection order between spaces. The BDF values of the experimental spaces in the three cases are above 0.9, indicating no apparent functional differences between the laboratory spaces in any of the cases. Thirdly, using the corridor as the only means of connection limits the potential organizational integration through spatial configuration. As is shown in Table 5, the integration of the laboratory space in T3-1 is lower than average (1.903), and the southwest (L7) and the northwest (L5) are the lowest (1.23). The cost of going to these two wings is higher than that of other wings due to the multiple transitions of corridors in topology. The same feature also exists in T3-2 and T3-3, in which there is a gap between the integration of the laboratory space and the transition space.

Finally, the transition space plays an important role in the building with high integration. Taking the corridor (C4) on the east side of T3-1 as an example, the total number of convex spaces is 124, with half (62) passing through C4 to reach the central public area. The high-frequency use of the transition space makes it one of the few places to create encounters except for the public space. Unless driven by a particular purpose or task, informal communication between researchers from different fields can only be triggered with a greater possibility at the junction of corridors and near the entrance.

5. Discussion

Space configuration that reflects potential social relations is the intermediary between the physical and cultural attributes of buildings, shaping the concept of community while inadvertently defining the identity and behavior of an individual [23]. This study quantitatively identifies the topology and spatial configurations of laboratory buildings in different periods, providing a new interpretation of the classical cases in history. The analysis method of space syntax used here is mainly based on the following points. Firstly, the analytical method of space syntax applied here allows for a deeper comprehension of historical design principles and the way in which the geometry of forms may be concealed in abstract experimental rules and physical characteristics, thus revealing the significance of spatial configurations for scientific activities. Secondly, space syntax can quantitatively describe the spatial structure of buildings, settlements, cities, etc. [37]. It has a broad scope of applications and can be used to reveal the genotypes inherent in laboratory space systems. Finally, the use of space syntax analysis methods here can make up for the lack of qualitative case studies to a certain extent. The combination of the two methodologies can promote the effective evaluation of laboratory typology.
Contemporary scientific research has become far more complex than in Galileo’s era, and the laboratory has changed dramatically in many ways compared to the past. Research issues and practical problems often require more than one researcher or discipline to address them adequately. With the complexity of scientific research and the mutual penetration of disciplines, face-to-face interaction among interdisciplinary teams makes scientific research an increasingly social activity. Promoting communication and stimulating innovation through space has become a focus in laboratory design today. The space that can only realize the basic functions such as experiments and teaching can no longer meet the needs. We need to consider the initiative of space itself and the relationship between space, scientific activities, and scientific development. Therefore, under the influence of new experimental needs and changing scientific concepts, it is important to examine the evolution process of the laboratory building.

6. Conclusions

The following conclusions are drawn from the above analysis:

(1) The evolution of the laboratory space in history was a process from closed to open, decentralization to centralization. The above cases from different periods reflect the remapped relationship between scientific research activities and spatial forms.

In the early days, when the classification of disciplines was not clear, the laboratory was a space spontaneously organized by individuals. Layouts of the laboratories were usually symmetrical, with a deep-branched tree form. The public space at the core was the most integrated.

With the rise of scientific revolutions, the corresponding practical space gradually became specialized and standardized. The internal connection became complex, with a shallow-ring bushy form in topology. According to different discipline requirements, the laboratory functions were further differentiated.

The laboratory buildings after World War II were usually generated by modules to adapt to the cooperative research between scientists. The transformation space had an unshakable position in the system, and the difference between departments was decreased, which is reflected in the high BDF value of the experimental space.

This study evaluates the data obtained through a comparative analytical approach, revealing the relationship between the space configuration and functional efficiency of laboratory buildings in different periods. It provides valuable information for analyzing laboratories for traditional or experimental typology and references for future laboratory design.

(2) The above analysis shows that the laboratory space has undergone a process from closed to open, decentralization to centralization. It is manifested in the increasingly large laboratory rooms and centralized layout, as well as repetitive units of departments. All of these have led to an evolution in the form of laboratory buildings, with a correspondence between the form and function of laboratory buildings in different periods.

(3) The analysis results emphasize the importance of the transformation space. From the topological perspective, the corridor is also an effective means to increase space depth and create private areas. It is easy to see from the previous analysis of T3-1 that two experimental spaces in the same case are likely to have differences in integration and intelligibility due to the local intermediary space conversion.

(4) In the analysis of cases mentioned above, it is found that the high spatial connectivity does not necessarily indicate that the case is distributed, as is the case of T3-3. The experimental spaces of each department are connected, which leads to efficient connectivity. However, globally, there are few choices for movement from one point in the space to another, acting in a conservative mode. Therefore, it is necessary to make a comprehensive judgment in combination with the degree of integration and justified graph.
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