

Research and Development Laboratories – Program Evolution

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Abstract This paper aims to provide general data and principles of research and development laboratories, which are the basis for architectural programming. The paper explores research and development laboratories through history, the roles and interactions between research and development, their character, and the activities they can encompass. It is divided into three parts. The first part refers to the definition of research and development laboratories and activities they can encompass (depending on the organisational structure of the company and/or field to which the laboratory belongs, it can cover a wide range of activities and encompass both science and technology). The second part, historical overview, is observed through the evolution of the relationship between science and technology, through the development of industrial research laboratories, and recently through the development of research centres that are connecting into larger spatial units we call technology parks. The evolution of the relationship between science and technology refers to the interaction between science and technology, and the three main waves of scientific interest and the way they reformulated laboratories. Development of industrial research laboratories is described using the example of Philips Natuurkundig Laboratorium (Nat.Lab.), and it's a transition from a simple laboratory near a factory in the early 20th century to a contemporary technology park. It is described how Nat.Lab.'s assignment and structure transformed over time in response to changes in context. The last part of the historical overview is talking about technology parks. New requirements and technologies led to the need for a different organization of scientific space. Following a

period of closed corporate structures, vertical specialization led to the collaboration between companies, academia and industry, which is the main characteristic of technology parks. The third part refers to the challenges modern laboratory faces today, the development trends and modernization of laboratory infrastructure, and the emergence of the new way of thinking and a culture of innovation. This study will facilitate understanding the relationship between research and development and other requirements that laboratories need to fulfil (e.g. development trends, such as the global market, teamwork, and the application of computer technology) when creating programs and designing modern laboratories.

Keywords Industrial Laboratory, Research and Development, R&D Lab, Living Lab

1. Introduction

Until the 19th century, the term "laboratory" had two meanings: the first referred to a room or a house where chemical research was carried out, and the second to a craft workplace [1]. At the beginning of the 19th century, natural science laboratories were established at universities [2], and at the turn of the 20th century, in addition to scientific and research laboratories, many "industrial laboratories" (Figure 1) appeared [3], whose research was focused on discoveries that could have commercial value. Today, the term laboratory¹ refers to a functional-organizational unit

¹ Laboratory – "one equipped for carrying out scientific experiments or procedures, esp. for the purpose of research, teaching or analysis; (also

equipped and arranged for conducting experiments and research. In the literature, we find the following classification of laboratories according to the type of use:

- teaching (practical training and teaching)
- research (basic and applied research)
- diagnostics / analytics (contract laboratory, process analytics), and
- development [4]

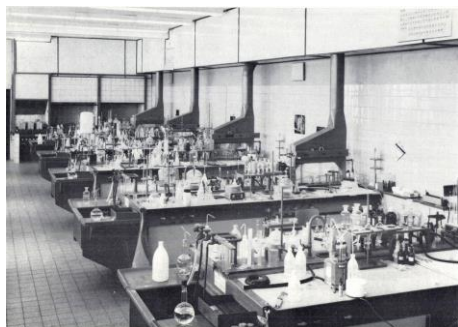


Figure 1. Industrial laboratory (chemical) in multi-story laboratory block WB in The Waalre complex of Philips Research Laboratories, Eindhoven, Netherlands, 1970. [6]

Different working methods, depending on the scientific direction, imply different program requirements and spatial-functional organization.

Teaching laboratories (Figure 2) are used for education in schools and colleges; they differ from research laboratories because they are used for teaching and they usually need to accommodate more people (they have more work units than a typical research laboratory, and the write-up area is located inside the laboratory) [7]. For example, experiments performed in chemistry teaching laboratories are like those in general chemistry laboratories, but the hazardous materials utilized will be less than those in regular chemical experiments [8].

Research laboratories (Figure 3) differ according to the scientific direction and activities they conduct. Basic research includes research in the natural sciences (chemistry, biology, physics, geology, etc.), while applied research (technical sciences, biomedicine and health, biotechnical sciences, etc.) applies the theoretical foundations of natural sciences.

Analytical laboratories (Figure 4) can be used to separate, identify and quantify matters. Usually, they are part of a bigger picture in which the analytical results may be used [9]. They can encompass chemical analytical laboratories, process analytics (analytical measurements in manufacturing process) and clinical/diagnostic laboratories (automated analysis systems). They are, in addition to specific analytical devices, recognisable by the preparation area (for example, a water control laboratory: water is sampled, reduced to a smaller volume in the preparation room, and then analysed in the analytical laboratory).

Development laboratories can be used for testing mechanical and other principles, developing specific solutions and/or products, and developing manufacturing processes (what exactly will be included depends on the nature, scope, and purpose of the laboratory). Sometimes they can have pilot plants (the main objective is to test the process developed in laboratories on a smaller scale) that simulate real-world conditions. They can have limited prototype production, smaller testing facilities, smaller in - process quantities, etc. This can involve a large variety of equipment and operations arranged in a continually changing design, and it is not possible to illustrate a comprehensive layout [8].

According to the field of activity, all mentioned categories have standardized requirements regarding spatial organization (in accordance with technological requirements). They represent a well-known design program that is adapted to specific requirements through interaction between the designer and user (researcher) [10]. In addition to these laboratories, which we classify by the type of use, there are also laboratories where functions and activities overlap, as in research and development laboratories (R&D lab) (Figure 5). Developed from industrial laboratories², they are focused on the research of new technologies, products, processes or solutions, i.e. their goal is the improvement of scientific knowledge and the creation of innovative products and services [11].

one in which chemicals or drugs are manufactured; an establishment in which such work is carried out" [5]

² Industrial laboratories and engineering methods were essential for transforming conceptual science research into products (goods or services) with socio-economic value. Development as a category is found in biology and social sciences in the second half of the 19th century, and the term begins to be used in industry in the late nineteenth and early twentieth century, where it denotes "the evolution of industry that can be achieved through research" [12].

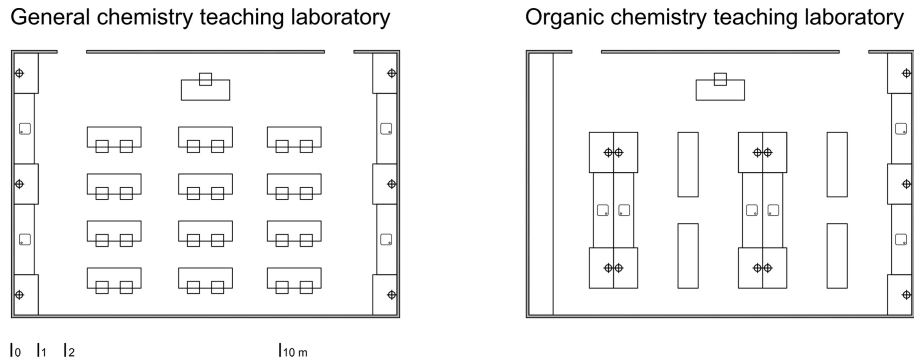


Figure 2. Schematic layout of chemistry teaching laboratory [8]

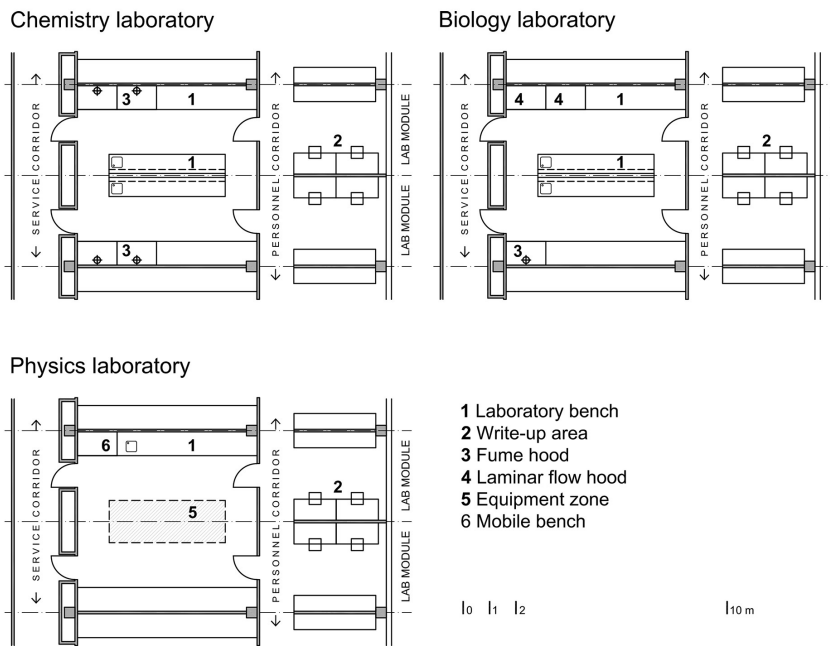


Figure 3. Schematic layout of standard double laboratory module with write-up zone outside the laboratory (source: authors)

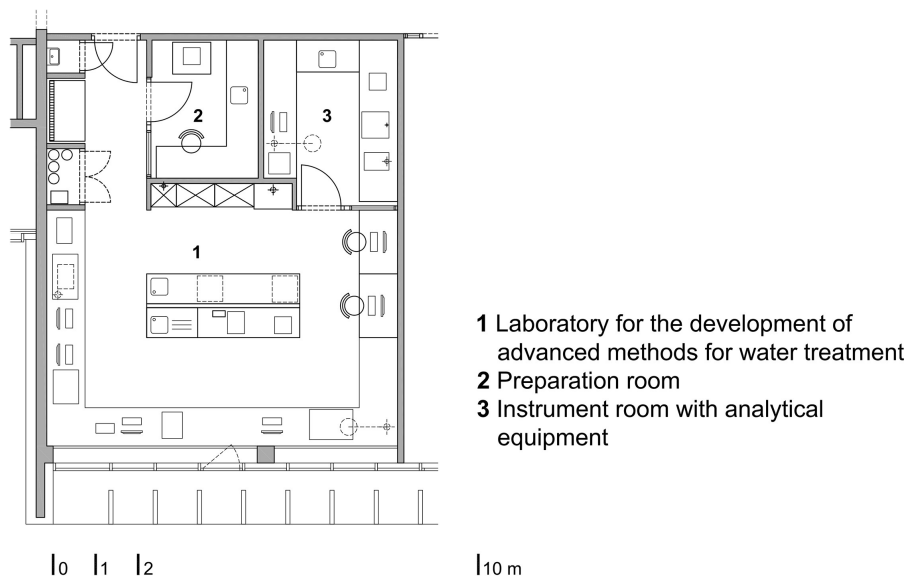


Figure 4. Laboratory for the development of advanced methods for water treatment (Analytical laboratory) in Research center Borongaj, Faculty of Civil Engineering, Zagreb, 2022., Authors: D. Dvornik and T. Peraković (source: author's archive)

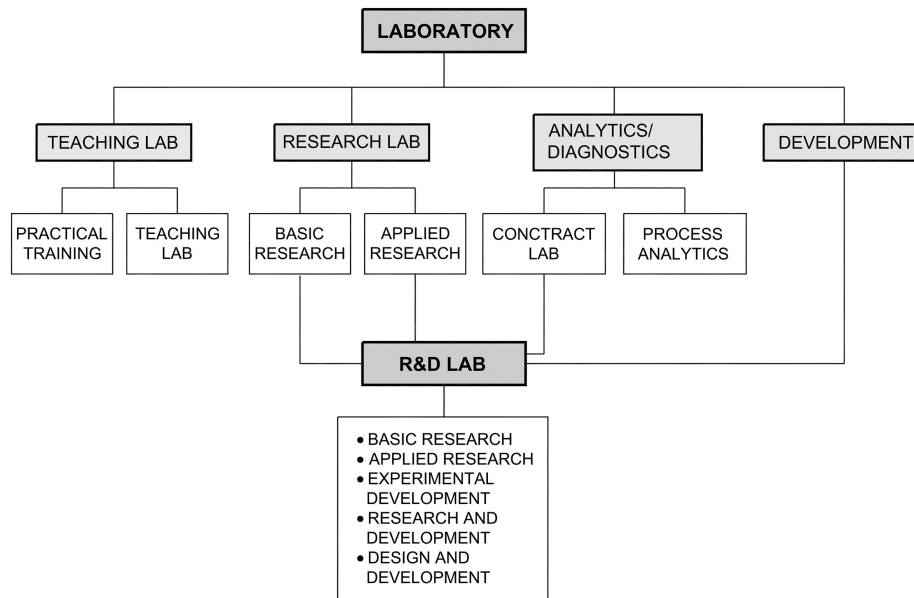


Figure 5. Laboratory classification according to the type of use (source: authors)

2. Materials and Methods

The materials and research methods have their origin in broader research conducted for the purpose of preparing a doctoral thesis on the *criteria for programming scientific and research facilities and architectural models of natural science laboratories*, which closely examine:

- classification by the type of use, scientific direction, working methods and spatial organization
- criteria for architectural programming (questioning specific problems of laboratory building in use) and will encompass interviews with scientists and comparative analysis of laboratory layout guidelines prescribed by the universities and research institutes, and
- flexibility / adaptability of laboratory spaces in relation to modern research needs

Research and development laboratories depend not only on the requirements of the research process, but also on the market and technological changes. There are research activities and processes that determine the specific characteristics of the architectural program. This research will deal with the architectural program, i.e. will encompass the starting phase of architectural programming by collecting generic data using conventional research methods like literature analysis.

The theoretical foundation of the research is based on a literature review of R&D strategies. Analysed papers show that companies use R&D investments to gain market share [13,14] and that product diversification can be a useful strategy for firms [15]. The discussion on the relationship between product-market competition and innovation goes back to Schumpeter (Austrian political economist, 1883-1950.), whose theory on economic growth, creative destruction, implies an endless struggle

between holders and new entrants [16]. R&D oriented companies were historically focused on specific areas, but nowadays the environment has changed (competition, ICT, sustainability issues) and they are facing pressure to constantly adapt to the new business environment. Enterprises are exploring new business areas, maximizing efficiency with vertical integration, and establishing a partnership [17]. They are increasingly forced to invest in R&D as a strategic response to market and rapid technological changes (this is pointed out within G7 economies, where firms operate under innovation pressure and global rivalry) [18].

The following research questions and research hypotheses emerged from the initial analysis:

- What are the specific characteristics of R&D laboratories that distinguish them from laboratories included in the classification by the type of use and what activities they encompass?
- What is the scope and purpose of R&D laboratories, what is their origin and what do they represent today?

The research hypothesis is that R&D laboratories represent a response to the dynamic competitive economic environment; they unify target parts of both research and development laboratories to minimize product development time. They are strongly influenced by development trends.

Sources of data for this research are predominantly academic journals and books (secondary data sources), but also laboratory blueprints and interviews with scientists and researchers working in various laboratories, including R&D laboratories (primary data sources). The tool of analysis utilized is thematic analysis and data interpretation included qualitative (contextual and descriptive) analysis.

3. Concepts and Definition of Research and Development

Research and development include a series of activities aimed at expanding and designing new applications of available knowledge [19]. Based on the conducted research (literature analysis and interviews with scientists), the following systematization of activities in research and development laboratories is proposed (depending on the organizational structure of the company and/or the field to which the laboratory belongs):

- basic research
- applied research
- experimental development
- research and development
- design and development

Basic research is experimental (or theoretical work) managed with the purpose of obtaining new discoveries about the observable facts and foundations of phenomena, without any specific application (properties, structures, and relationships are analysed with the focus of proposing and evaluating hypotheses, theories, and laws) [19].

Applied research is experimental work taken to obtain new knowledge and is primarily focused on a specific, practical goal (or object). The results of applied research are primarily deliberated for application to products, operations, methods, or systems [19].

Experimental development is just one possible phase in product development³ [19]. It may cover testing the basic physical capabilities or a new principle of operation of a mechanism for a specific purpose, but is not necessarily associated to a product, or it is carried out for validation purposes. Generic knowledge is tested for a specific application [19]. It is followed by a step of concretely transferring this knowledge to product development. The order of occurrence of research and development activities does not mean that basic research leads to applied research, which in turn leads to experimental development [19].

Research and development can include experimental development and/or development with testing or development of minor details. Traditional models of research and development follow a linear process similar to the stages of new product development (the process begins with basic research, then follows applied research that addresses a specific problem or question, followed by development and preparation of the product for commercialization, especially engineering, testing, manufacturing and support) [11].

Design and development use existing technologies and

knowledge to develop a product or a new combination of products; they are focused on the practical application of ideas during research and development. This phase involves creating and refining a product, system, or process based on research results (ensuring it meets user needs and is feasible for production), including prototyping, user testing, and finalising production specifications.

R&D laboratories can encompass both science and technology to meet the demands placed upon them, and, as they cover a wide range of activities, their programs and layouts may also depend on the field they belong to and the company's organizational structure.

4. R&D Lab – Historical Overview

Industrial research laboratories, as was mentioned above, serve as a place where science and technology can communicate; here, scientific research is carried out for the purpose of technological development⁴[3]. Applied and commercialized research today differs from the early 20th century and postwar research [21]. According to this, a historical overview can be observed in the evolution of the relationship between science and technology, through the development of industrial research laboratories, and, recently, through the development of research centres that connect into larger spatial units we call technology parks.

4.1. The Interaction between Science and Technology

The science and technology relationship is complex, though interchangeable, and often differs across fields and phases [22]. Three main waves of scientific interest flooded corporate organizations, and each wave reformulated their laboratories, discovering new aspects of industrial research and the inner relation between science and technology [23].

Initially, the interaction is direct and informal, science and technology are integrated, and science is the driving force [3]. This relationship allowed simple transfer of ideas but did not provide a good mechanism for technological development (at that time, most laboratories worked toward interaction due to social and economic circumstances) [3]. The activities of a research laboratory are almost indistinguishable from those of factories, which allowed the company to enter new products and technology areas [3].

In the second type of interaction, the laboratory is a place where scientists can conduct research based on their personal interests (akin to an ivory tower) [3]. Science and technology are distinct, and technology results from the

³ Product development includes the entire process from idea and concept formulation to commercialization [20]. In corporations, most product development takes place within a strategic business unit that is responsible for its own profit and loss, aligned with industries, and has a well-defined value chain and distribution channel for customers. The process starts with a vision of innovation that is in line with the strategic business unit [20].

⁴ Gilles Hols (director of Philips Nat.Lab. from 1914-1946) describes an industrial laboratory as an organization where problems relevant to industry are investigated using scientific methods and instruments [25]. In an industrial laboratory, where a problem is given, it is necessary to provide appropriate tools [25].

selection and development of ideas that arise from scientific research. In this case, inventive individuals came up with ideas for new products or technologies without the request of a business group. Industrial research laboratories operated this way in the 1950s and 1960s, driven by the belief in the importance of basic scientific research [3].

The third type of interaction is customer-oriented service; scientific research is conducted for technological development. In the 1970s, the socio-economic conditions changed: economic growth slowed, criticism of technology arose, and customers became more discerning [24]. In response to these problems, contract research and new financing model for the research program were introduced – largely from the production department's targeted research budget. With these changes, we see that the R&D laboratories no longer produce dramatic revolutionary innovations but rather make numerous smaller contributions to product development [3].

4.2. Development of Industrial Research Laboratories

Since 1970s, big companies have retreated from research, and nowadays we have a system in which start-ups and small teams (private sectors or academics) do most of the innovation in the early stage [26]. In recent decades, it has been returned to co-creation from central research laboratories due to the integration of separate disciplines (in early years of industrial research, this was the case because of resource scarcity) [27].

In the late 18th and 19th centuries⁵, industrial companies grew and established departments for various activities: production, distribution, finance and research and development [24]. The decision to organize research and development within the company was also supported by the idea that such laboratories would serve as repositories of knowledge, information, and skills [28].

In economic studies, this act is seen (according to Schumpeter) as an attempt to disorder economic balance. It suggests that the business owner is in the primary stage of economic growth (later, Schumpeter declared that inventive entrepreneurs were supported by economic institutions and firms with funds to realize their vision) [29].

Laboratories in the early years carried out a wide range of tasks and served as a multipurpose facility [30]. They were of a hybrid nature; they performed tests and measurements for quality assurance, solved production problems, and conducted research directly related to improving existing products and/or developing new ones [24]. Usually, they were attached to factory plants and

were small brick chambers or huts (poorly equipped and fitted with utilities at the end of the 19th century) [31].

The further development of industrial research laboratories was associated with the expansion and diversification of manufacturing companies' activities and products [32]. Also, in the late 19th century, intellectual property protection was strengthened, further encouraging the establishment of industrial research laboratories [33].

In the 1860s, a revolutionary new laboratory layout (like the laboratory we all know today) emerged [31]. First appeared at German universities and later spread worldwide [31]. It included rows of wooden benches (arranged in two rows, with a passage between them) with storage cupboards underneath and bottled racks above [31]. The benches were equipped with a gas pipeline and flowing water with sinks. Along the walls were fume cupboards [31].

At the turn of the 20th century, many "industrial laboratories" emerged. In Europe, it was connected to the expansion of dye production (should be observed in the context of modern chemistry) and in the USA, to the telecommunication and electrical industries [35]. Also, at that time, large-scale laboratories were established, usually in military complexes [35]. The period between 1930 and 1970 is marked by central research laboratories [27].

After World War II, new type of instrumentation was introduced into laboratories (partly due to wartime developments) [31]. These new instruments (infrared and ultraviolet spectrometers, nuclear and magnetic resonance spectrometers and mass spectrometers) first appeared in physics and later in chemistry laboratories, and they had a variety of uses [31]. They didn't radically change the laboratory layout, partly because classic chemical laboratories already had specialized rooms, which could be reused for new instruments. These laboratory buildings usually had a large basement, mostly for a power plant and storage [31].

In 1980s, open structures (organizational aspect of early years of industrial research) were brought to life following a phase of relatively closed corporate structures (vertical specialisation led to global collaboration between companies) [27]. The 1990s marked the beginning of adaptable, dynamic structures in corporations, and since the 2000s, academia-industry collaboration and the rise in start-ups have increased [27].

Around the end of the 20th century, a second revolution in laboratory design occurred (escalating safety and health standards) [31]. A new laboratory feature included a relatively small laboratory with benches (or fume hoods) on each long wall and benches in the middle [31]. The building layout features laboratory spaces in the middle, the enclosing wall facing the office spaces is transparent [31], and the other wall opens onto a corridor with specialised rooms [31]. This layout made the instrument rooms more accessible in contrast to previous isolation from the laboratory [31]. Also, by this time, it was

⁵ Industrial research historians have found numerous scientists contributing to the new technologies and industries in the early 19th century, but individual instances didn't create a significant pattern of science applied to industry until the late 19th century, when telecommunication, electrical, and chemical industries began to emerge [34].

recognised that the rational design should be flexible (easy to convert), and the utilities should be easily accessible for maintenance [31].

Below, the development (and present situation) of the relevant R&D laboratory is explored using the example of Philips Natuurkundig Laboratorium (Nat.Lab.). It is selected because of the transmission from a simple laboratory near a factory in the early 20th century to a contemporary technology park, and this process is relevantly researched and elaborated in literature with expertly processed data.

Nat.Lab.'s assignment and structure transformed over time in response to changes in context. But through time, it remained a place for multidisciplinary research [29].

This, originally a physics laboratory, was founded in 1914 and conducted basic research to improve existing products [36]. Nat.Lab. was of a hybrid nature [36]. It covered basic research, development and testing, problem-solving in production, and was also closely connected to the factory [36]. The first laboratory building was located near the factory. From 1923-1924, the research moved to a new laboratory building (in the Strijp district of Eindhoven) whose floor plan shows that several research areas were already in place (Figure 6) [36]. In the history of Philips Research Laboratory, two transitions occurred: one after World War II and another in the early 1970s. The same transitions have been identified in other laboratories (General Electric GE, Siemens, DuPonts Lab) [36].

In the first part of its history (1923-1946), the main goal of Nat.Lab. was to gain knowledge through basic

research to achieve product diversification (company management decided to introduce new products) [36]. After the laboratory moved to the Strijp district, it began to grow rapidly. The floor area increased from 2,700 m² in 1924 to 17,700 m² in 1930 [36]. The Strijp district originally occupied a peripheral area in the city, but it was not an isolated industrial district; it was surrounded by a large labor-housing estate, connecting it to the city's fabric.

In a short period, the physics laboratory (Nat.Lab.), the machine and phyllite factory, and several manufacturing structures for manufacturing were erected. The "E-shaped" Nat.Lab building belonged to the pavilion typology (Figure 7), and it played a principal part in the development of Philips [37]. The laboratory conducted measurements to assess the quality of the light bulb (a Philips product at that time) and, at the same time, studied the natural phenomena of light bulbs to improve them. With the further expansion of the product range, the laboratory embarked on research related to these areas [24]. During this period, Nat.Lab. also embraced pilot production, setting up smaller-scale production lines to experiment with production and obtain the expertise needed for potential enhancements and larger-scale production [36]. In the 1920s, the Philips company grew dramatically, but in the 1930s, growth was halted by the economic crisis (drastic reorganization was carried out) [29]. At the same time, the company benefited from the radio market, which mitigated the impact of the crisis (later, it became apparent that product diversification was a good strategy for addressing the economic crisis) [29].

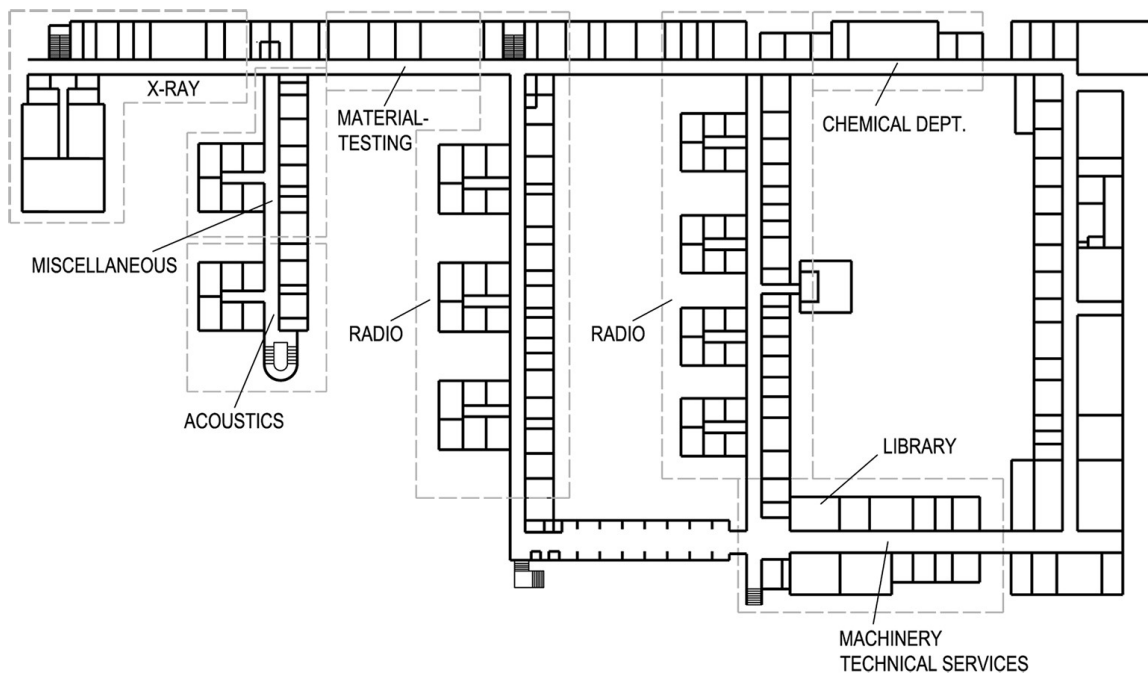


Figure 6. Scheme of the extended Nat.Lab. in 1926. (source: adapted from [36])



Figure 7. Nat.Lab. in 1930s [38]

In the second part of its history (1946-1972), the goal of Nat.Lab. was to understand natural phenomena (basic research) that could later be applicable for developing new products and improving existing ones [36]. After World War II, a period of economic development started (by 1950s, the damage caused by the WWII had been repaired). Philips continued its growth, which had been halted by the war [29].

The size of the laboratory also grew during this period. By 1944, the floor area of Nat.Lab in the Strijp district of Eindhoven was 20,000 m², and from 1952 to 1955, the floor area increased from 25,620 m² to 27,920 m² when an entire new wing was built [6]. In 1963, the laboratory moved to new premises in Waalre (Figure 8) (The Waalre complex in a suburb south of Eindhoven). At that time, it was considered that scientific research in an industrial laboratory should be flexible, not only in the layout of the complex but also in individual buildings and technical services (to accommodate continuously changing requirements) [6]. The idea was to divide the complex into separate sectors, each consisting of a universal laboratory (Figure 9), several specialized laboratories, and a workshop. Also, personal contact between staff across branches was considered important [6], and the researchers' requirements were incorporated into the design of the new premises [36]. Laboratories could conduct basic research (with uncertainty of outcome) because sufficient funds were available, and there was continuous interest in new scientific developments⁶[24]. In this period, all newly manufactured products were sold, and it was assumed that the more research and development was invested, the more products were produced [39]. Departments for new products were established - New Product Division (PD), each of which had its own development laboratories [24].

In the third part of its history (1972-1994),

Nat.Lab.'s goals switched to the needs of the Product Division (PD) rather than reflecting its own ideas about new product development (there was a stricter selection of new research). Research was more focused on developing new products and meeting market needs, and Nat.Lab's resources became limited [36]. The reason for these changes in the strategy of industrial research laboratories lies in the economic and social changes of the second half of the 20th century [24]. The economic boom was coming to an end, awareness of the negative effects of technological development was growing, and companies could no longer afford to bring any products to the market [24].

From the USA and European standpoints, the companies faced increasing competition from Japan, and questions were raised about their in-house laboratories (the R&D unit was not the only option for corporations to stay innovative). Internal and external impacts affected the corporate laboratory, and it became oriented towards business-driven activities [29].

In the late 1990s, Philip's R&D activities were spread across Eindhoven. In 1999, the company's board decided to establish the Philips High Tech Campus in the Nat.Lab. complex, to centralize the development activities of all Philips production departments [40]. To strengthen interaction among people with varied, specialized expertise, Philips made available the campus to other companies in 2003, renaming it High Tech Campus Eindhoven⁷ (Figure 10) [40]. In March 2012, the campus was sold to a private investor. Philips stays on the campus, but its status has changed from owner and manager to inhabitant. The campus lures companies and research institutes engaged in ICT and research and development [40].

One of the key goals of the campus is cooperation between companies and collaborative R&D by providing an approach to innovation services (for example, material testing, production facilities for electronics, product certification, etc.) and creating an innovation ecosystem that increases the transfer and exchange of information and experiences between the companies and institutes on campus [41].

The physical spacing between buildings on campus is minimal to facilitate direct interaction and provide easy access to technological facilities [41]. The central area of campus, which hosts numerous facilities (restaurants, conference rooms, market, and fitness centre), has been intentionally planned to connect people and foster collaboration (other buildings do not have any restaurant, which encourages people to often visit the central area) [41].

⁶ After World War II, there was a belief in the contribution of science and basic research to technological progress (the application of nuclear physics in war). The US President's science advisor played a key role in the general attitude towards basic research with his postwar report "Science: The Infinite Frontier", where he stated that basic research always ultimately results in technological progress [24].

⁷ High Tech Campus Eindhoven covers 100 ha, over 90 different companies and more than 7,000 people. The campus has developed into a dynamic mix of techno start-ups, small- and medium-sized enterprises, service companies, technology institutes and multinational companies [41]. The preferred approach of working on campus is "Open innovation", which means that companies on campus share knowledge, skills and "R&D" infrastructure (in the tradition of the original Nat.Lab.) such as laboratories, clean rooms and equipment to achieve faster, better and more customer-focused innovation [41].

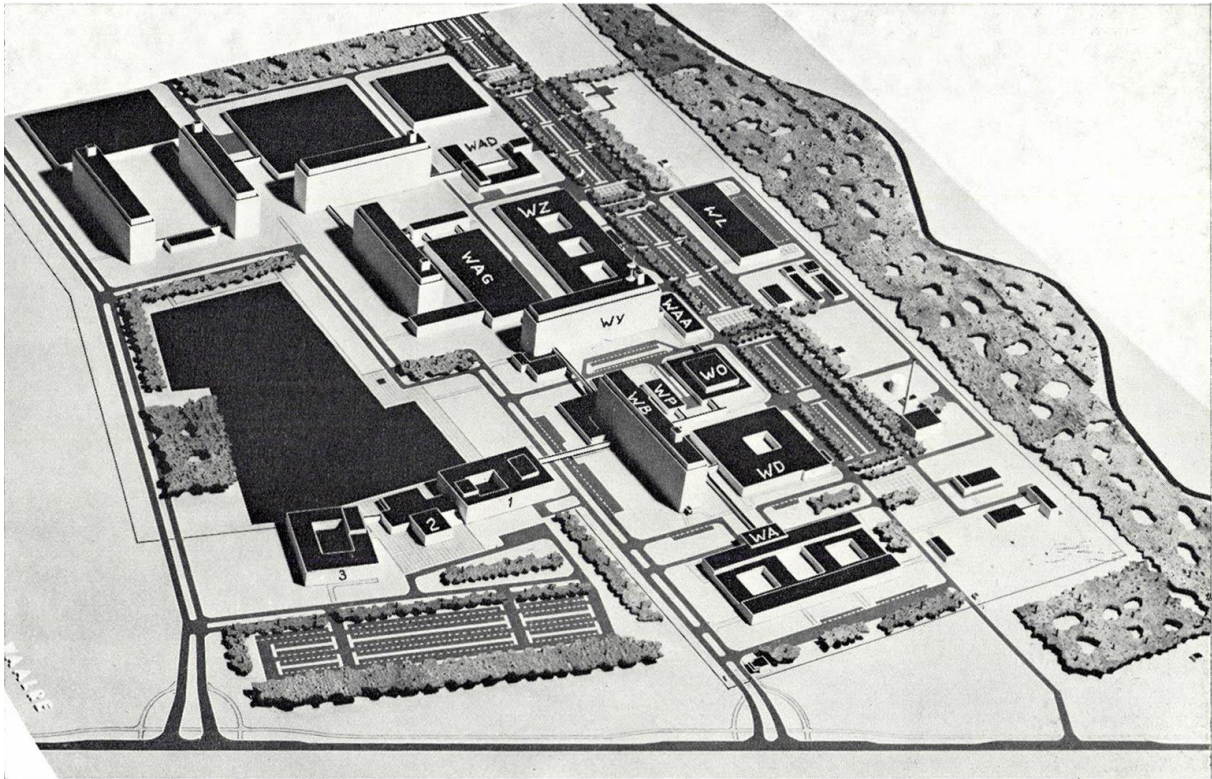


Figure 8. Waalre Complex model, 1968. Model illustrating current plans, the most important buildings in use or being built are marked by their code letters. The first laboratory building to be erected, building WA (1958.) was a specialized laboratory designed for technological research. The building was a pilot project to provide experience with equipment, ventilation, and utilities. The setting of the laboratory was planned with the landscape and inner garden courtyards. After, multi-storey blocks WB and WY with universal laboratories were built. [6]



Figure 9. Waalre Complex, 1968., Laboratory buildings WB and WY [6]

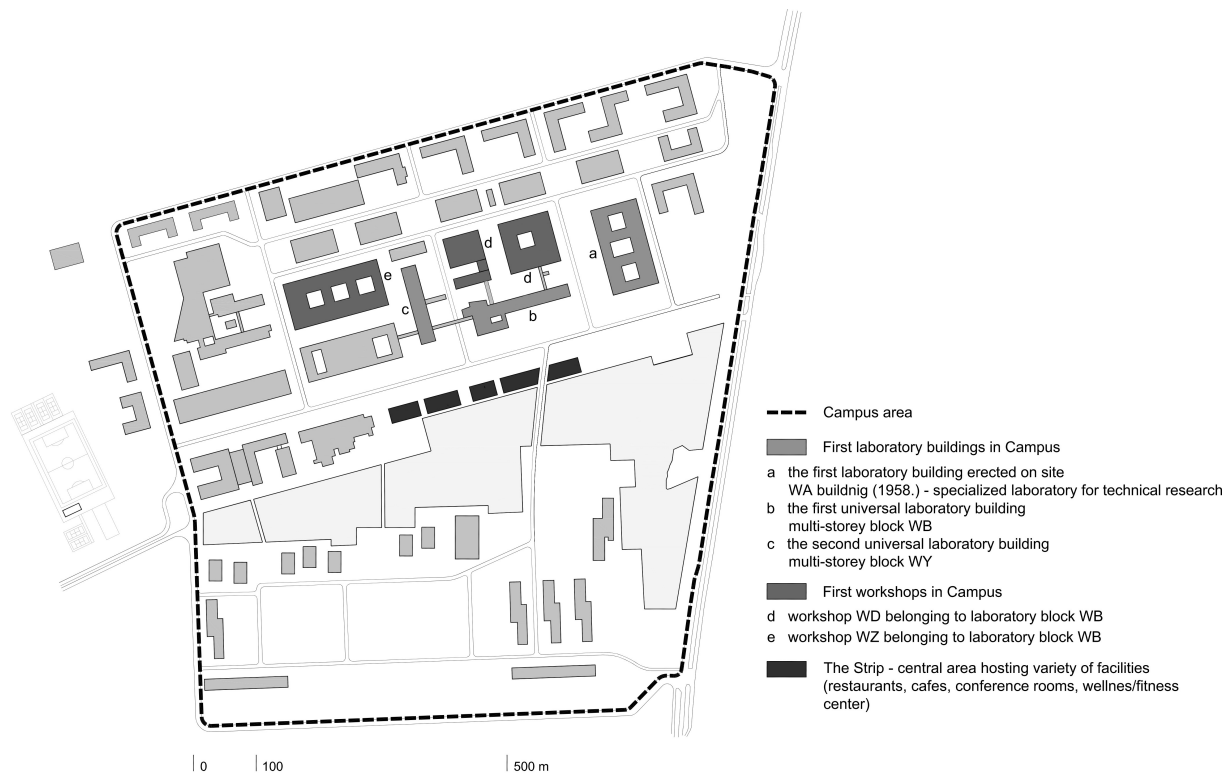


Figure 10. Scheme of High Tech Campus Eindhoven today (source: adapted from [6] and [42])

4.3. Development of Technology Parks

The R&D laboratory, like all organizational systems, evolves and changes over time, and market and political influences tailor the organization and its actions [43]. The research and development perspective adapts to the context and conditions, and at the same time, R&D processes can be essential in dealing with these changes [39]. New requirements and technologies necessitated a different organization of scientific spaces. Philips Nat.Lab. has undergone a transition from a simple laboratory near a factory through a central research laboratory to an open structure and technology park. After a period of closed corporate structures, vertical specialization led to collaboration between companies, and academia-industry collaboration [27]. This academia, industry and government collaboration is the main characteristic of technology parks, which first appeared in the 1950s with the establishment of Stanford Research Park and developed in the 1980s [44]. Their main task is to support innovative activities and commercialize the results of scientific research [45].

The first generation of technology parks was established by universities (in the 1950s and 1960s, most were leased to technology companies) to expand the university's economic opportunities. Second-generation technology parks can also be considered an extension of the university, but they are not by definition in proximity or subordinated to its exclusive oversight. The third generation of parks (modern technology parks) is established in urban regions and emphasizes the built environment and spaces that

stimulate creativity [46].

What is recognized as different and original in terms of organization is that technology parks require stimulating surroundings [47]. They are usually located in suburbs or next to universities and research institutes, and the park's function is not restricted to the creation and transfer of knowledge; as an innovative urban element, it also impacts the local and regional environment [48]. Some of the main spatial characteristics of technology parks are: location next to a knowledge base, accessibility (good transport connections), clarity (the park area is clearly visible within the urban area), facilities within the park (administrative and public, business, service, residential, sports, entertainment), and landscape (peaceful and natural environment) [48]. They draw attention because they have successfully combined an enabling environment, economy and applied technology. Universities, government and the private sector have used this new urban typology to foster innovation and development [48].

5. Future and Development Trends

Modern laboratory building layout, in terms of space relationships, is divided into "clean" and "dirty" areas. The "dirty" laboratory work (laboratories and instrument rooms) is separated from the "clean" office areas and the shared spaces [31]. Heightened health and safety issues have already affected a laboratory design, and, if we assume that this could remain dominant, with the tendency to work at

home, the future may lie in robotics (some work in labs has already been largely automated) [31].

Nowadays, as science accelerates, some principles are emerging for laboratory design: designing from inside out (designing around laboratory workflows and production suites), flexibility, strategic planning [49] and emphasis on the user and user perspective.

In the globalization era, innovation⁸ is an essential for economic development and maintaining competitiveness [50]. The concept of innovation includes new technological, economic, organizational and social solutions [51]. Innovation in R&D laboratories involves creativity and originality, applying effective processes, and utilizing new technologies [52]. Over the past decades, the concept of innovation (initially an unstructured process [27]) has gradually changed from a linear process to a flexible, agile process structure [27], and now completely new innovations such as frugal innovations or organic innovations are emerging [51]. Under market pressure, information technologies and globalized science companies are constrained to consider their R&D strategies [53]. In line with these trends, research and development are transforming to achieve more with fewer resources and faster. An emerging trend in corporations is the use of alliances, collaborations and outsourcing as a substitute for internal research and development. R&D organizations are restructuring and downsizing to increase efficiency and productivity and shorten time - to - market [54] (the organization must be able to read and interpret technical and sociological forces of changes in the context of the corporation's strategic needs and capabilities [55]). One possible way to respond to these pressures is to seek partners and establish collaborative networks [55]. Corporate R&D is becoming more connected and informed (not all R&D done by the firm will be done in-house). To house this ecosystem, new structures are emerging: firm networks (R&D lab with extended link-outs), industry-wide cooperation, and virtual networks (shared resource networks) [53].

Accordingly, the term open innovation has emerged, denoting a situation in which an organization does not rely solely on its own expertise and knowledge, but uses multiple external sources, such as customer input, published patents, and external participants to stimulate innovation [57]. In addition to the innovation focused on individual users and their needs (this can exclude broader

context), sustainable-oriented innovation is also emerging (it considers environmental, social and economic impacts) [58]. Their dynamic and outcome are shaped by the space in which they can take place (physical or virtual spaces). Physical space can be adapted to accommodate different requirements, fostering direct interaction and encouraging communication. Virtual spaces use digital tools and offer flexibility in time and location [59].

An interdisciplinary approach is found in a growing number of research programs, with researchers increasingly working across disciplines, domains, and boundaries [60]. Development trends emphasize the flexibility of laboratory buildings and influence spatial organization: global markets, teamwork, an emphasis on the user and user perspective, and the application of computer technology [7]. Technologies such as artificial intelligence, robotics, automation, and web-based databases enable new forms of research [61]. Data sharing accelerates the pace, allowing researchers to use relevant data and create opportunities for new collaborations [62]. These technologies influence not only the way scientists work but also impact the laboratory and supporting spaces [63].

Big data can accelerate the innovation process and benefit companies economically, but it also raises concerns about data security and privacy [64]. The amount of data is expanding rapidly, and companies are seeking to better understand how to collect, manage, and interpret big data [64]. For these reasons, it is necessary to provide considerable support spaces for servers and employees to process this data.

Today, the user plays a key role in the innovation process (since mid-1990s, institutions have begun to consider "citizen participation" a necessary policy in the field of research and innovation [65]), emphasizing the importance of openness, collaboration and a user-centred approach to future innovations [66]. The academia is aware of the need to bridge basic research and real life and create new forms and formats of laboratories, such as living labs [66]. Living labs are conceived as a development and testing of products in a real-life environment, and in terms of scale, they range from a single-building experiment (Figure 11) to a city-wide initiative [67]. As they seek to replace the experimental and controlled approach of a conventional lab with real-life surroundings, their spatial condition tends to encourage or hamper cooperation between participants [68]. They connect stakeholders across all sectors (companies, universities, government and users) who cooperate to create, prototype, test and deploy new technologies, services, products and systems in a real-world environment [69]. They vary from a common research framework by placing users and stakeholders as active participants in the centre of the innovation process, rather than merely as subjects of testing [70]. They highlight that users and stakeholders can be engaged in co-creation [71], and that the actual value of innovation lies not in superior technical qualities but in its alignment with

⁸ Schumpeter explains innovation as the creation of a fundamental or radical change that involves the transformation of new ideas or technological inventions into a market product or process. It emphasizes the economic and technical nature of innovation and defines four types of innovation: product innovation, process innovation (the introduction of a new way of production), organizational innovation and market innovation [56].

Innovations as a process and organizational change do not necessarily have to result from new scientific discoveries; they can combine existing technologies or their applications in a new context [50].

Innovation involves more than R&D. Effort that goes into the introduction of new products may include conception, primarily knowledge generation (research, advanced development, basic invention), product design and engineering, getting ready for manufacturing, manufacturing start-up, debugging production, marketing start-up, and probing the market [22].

users' needs [72].



Figure 11. Living Laboratory (a exterior, b interior) – Mobile Nzeb house (Project Manager: B. Milovanović) called MUZA (Mobile Efficient, Healthy Architecture) – resting construction according to NZEB standards, where visitors will be able to learn about NZEB and experience NZEB first-hand. MUZA conducts measurements of indoor environmental quality parameters, such as temperature and relative humidity, CO₂ concentrations in the air, relative air quality, and measurements within the layers of the building's outer envelope, Zagreb, 2021, Authors: N. Vezilić Strmo and M. Sladoljev (source: author's archive)

Innovation is moving from technology parks⁹ and university campuses to urban innovation districts – the urban environment can become a testbed for research and development experiments (e.g. testing smart urban infrastructure); city districts can become living laboratories for research in the digital and tech realm that has a social or spatial dimension, especially in the areas of robotics, machine learning and automation [63].

Today's era is defined by digitalization and networking. In such a process, it is important to gather different perspectives, which can lead to the successful development

⁹ Technology parks with a high concentration of technology tested in-situ have been the starting points for the development of smart cities. Smaller urbanized areas with multifunctional facilities have served as a test-bed for the implementation of high-tech systems (for example, for public transport), and these tested systems can be used to modernize the infrastructure of existing cities through the integration of information technologies [47].

and implementation of new ideas.

Ideas focused on user participation are not new, but the complexity faced by today's laboratories and the future laboratory shows a qualitatively new level [66]. These new formats of future laboratories speak of the modernization of laboratory infrastructure and the emergence of a new way of thinking and a culture of innovation [66].

6. Results and Discussion

The main characteristic that distinguishes R&D laboratories from laboratories classified by the type of use (teaching, research, analytical and research lab) is their hybrid nature. They have retained their hybrid character, and depending on the purpose, scope, and size of the laboratory, they can encompass both science and technology with a wide range of activities from basic and applied research, experimental development, R&D, to development.

The concept of a research and development laboratory has evolved through changes in the research process and work organization. Since the beginning of the industrial age in the 19th century, industrial research laboratories were of a hybrid nature. After they went through the transition from product-driven laboratories focused on basic research to the new living laboratories that connect the public and private sectors and users in the creation and testing of new products and services in a real environment.

Laboratories in the early years (19th century) carried out a wide range of activities (they dealt with basic research, solved problems that arose in production, carried out tests and measurements for quality assurance, and there was also research related to the improvement of existing and/or further development of new products). It was usually a smaller building, of simple construction, with a minimal standard of equipment, which was attached to the factory.

The R&D laboratory's mission at the beginning of the 20th century was to gain knowledge through basic research to achieve product diversification. The laboratory layout included wooden benches arranged in two rows, with a passage between them (the benches were equipped with running water, gas and sinks). After World War II, laboratories continued basic research (which could be useful for developing new products and improving existing ones). A new type of instrumentation was introduced in laboratories (spectrometers) because of wartime development. These specialized rooms didn't change laboratory layout much, since the classic chemical laboratory already had instrument rooms.

In 1950s, after a period of closed structures, collaboration between companies, academia and government emerged, marking the beginning of the development of technology parks. Initially, their goal was to expand the economic opportunities of the university, but modern technology parks are established in urban areas and emphasise the built environment and spaces that

stimulate creativity (some of the main spatial characteristics of technology and research parks include location near knowledge base, good transport connections, diverse facilities within the park and landscape)

Since 1970s, research has been more focused on developing new products and meeting market needs. It was considered that, as in scientific research, building layout and technical services should be flexible to accommodate continuously changing requirements. At the end of the 20th century, due to health and safety requirements, a new laboratory layout was introduced. The layout was divided into “dirty” (laboratory and instrument rooms) and “clean” areas (offices and shared spaces). The building layout contained laboratory spaces in the middle, outer wall, facing office spaces were transparent, and the other wall opened onto a corridor with specialised rooms (making the instrument rooms more accessible in contrast to previous isolation from the laboratory).

Nowadays, as science accelerates, some principles are emerging for laboratory design: designing from the inside out (around laboratory workflows and production suites), flexibility, and strategic planning. New technologies such as AI, robotics and databases, enable new forms of research; they affect not only the scientist’s work but also the laboratory and support spaces (for example, the amount of data is expanding rapidly, and companies are seeking to better understand how big data can be collected, and it is necessary to provide considerable support spaces for servers).

Since 1990s, institutions have started to consider “citizen participation” a necessary policy in research and innovation, and today, users play a key role in the innovation process. The idea is to bridge basic research and real-life and to create new forms and formats of laboratories, such as living labs. They aim to replace the experimental and controlled approach of traditional labs with real-life settings, and in terms of scale, they can range from a building to a city.

Development trends lead to overlapping functions and activities, and R&D laboratories respond to a competitive economic environment. They aim to unify target parts of research and development laboratories to minimize product development time, which makes the design program more complex.

The analysis of research and development laboratories in the socio-economic context shows the influence of political and market factors, of different research and development models, and, consequently, of the research process and laboratory programs.

From the perspective of architectural program, it can be very complex because of the dynamic relationship between research and development on the one hand, and political and market influences and development trends on the other. In addition to being places of scientific discoveries and the development of new products, R&D laboratories can also generate economic and spatial development, whether located within the city’s urban fabric or in technology

parks.

7. Conclusions

The conducted research has shown that an understanding of concepts of modern research and development laboratories is necessary to design a quality architectural program. Research and development laboratories have been of a hybrid nature from their beginnings to the present day. They have evolved from industrial research and development laboratories adjacent to factories, through central product-oriented laboratories and research centres (connected into larger spatial units), to living laboratories integrated into the urban fabric.

An additional specificity is that research and development laboratories are strongly influenced by development trends, and they represent a response to a dynamically competitive economic environment. To reduce product development time, they unite the target parts of both research and development laboratories. Due to their very nature and the relationship between science and technology on the one hand and development trends on the other, new research and development laboratories are continuously emerging.

In addition to the predictable need for modernization of laboratory infrastructure, they also indicate the emergence of new perspectives and the growth of a culture of innovation, and although each laboratory is custom-made, it is necessary to consider its bigger picture, that is, to define its common features and impact on the surrounding context.

The analysis of research and development laboratories, from the perspective of architectural programming, indicates their lively changeability because of the development trends, internal activities and connections, which requires continuous further research into the criteria for programming research and development laboratories.

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