1

The Lab of the Future

1.1 Presentation of the FutureLab.NRW Concept

1.1.1 The Inspiration

In 2016, we had the opportunity to develop a new concept for our laboratory at the Institut für Umwelt & Energie, Technik & Analytik (IUTA), an affiliated research institute of the University of Duisburg-Essen. This involved modernizing the infrastructure, including the analytical instruments, IT, and software. Our inspiration for the FutureLab.North-Rhine-Westphalia (FutureLab.NRW) came from the presentation of the SmartLAB at LABVOLUTION in Hannover [1]. The new concept featured hexagonal lab furniture, smart glasses, and robotics. We were unable to find any of the technical approaches displayed there in our laboratory, nor did we receive any notice from academic or industry laboratories that had incorporated these new features. This led us to develop our own future lab, which is based on the analytical methods and workflows we have developed over the past 10–20 years.

1.1.2 The Starting Point

1.1.2.1 Instrumental Analysis for Small Molecule Quantification

At the beginning of the new millennium, triple quadrupole mass spectrometry coupled to high-performance liquid chromatography (HPLC) (LC-MS/MS) was a young technique. As the technology matured, it began to gain acceptance in routine laboratories. Over the next 5–10 years, it became the gold standard for life science applications. Now, the food industry, the pharmaceutical industry, the environmental sciences, and the forensic sector rely on this technology.

LC-MS/MS is uniquely suited to analyze and quantify target analytes in very complex matrices at the ultra-trace level [2]. We have used the technique for the trace analysis of very potent and toxic chemicals. One of our analytical departments is involved in projects focused on cleaning strategies in oncology pharmacies [3–8]. Very potent chemicals, known as cytostatics, are still used to treat cancer patients. The negative side effect is that these molecules are themselves carcinogenic, mutagenic, and toxic

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to the reproductive system. They are therefore called carcinogenic, mutagenic, or reprotoxic (CMR) agents.

In chemotherapy, drugs are administered by infusion. For this purpose, a solution containing the active pharmaceutical ingredient is prepared in oncology pharmacies. The person who carries out all the steps to properly prepare the infusion solution must wear personal protective equipment, as is shown in Figure 1.1. The entire process is performed in a safety cabinet with laminar airflow and additional filtration systems.

This means that all the technical requirements are in place to ensure the safety of the operator. However, accidental contamination, or spillage, cannot be completely eliminated. Cross-contamination of laboratory areas can occur if gloves are not disposed of as recommended by safety guidelines, or if shoes are contaminated without the laboratory staff being aware of it. In 2000, Kiffmeyer et al. published a paper showing that a computer keyboard next to a safety cabinet used to prepare cytostatic solutions was highly contaminated [9]. The reason was that the laboratory staff did not change their gloves when entering data for documentation. Accidental contamination of offices is still a serious problem because many laboratories use paper-based documentation.

Since then, we have devoted considerable effort to develop highly sensitive methods for the trace analysis of these compounds. The first analytical methods we developed based on LC-MS/MS included only a limited number of target analytes [10–12]. Our main focus was on the analysis of cytostatic and anticancer drugs to improve cleaning procedures in pharmacies. A few years later, we used LC-MS/MS

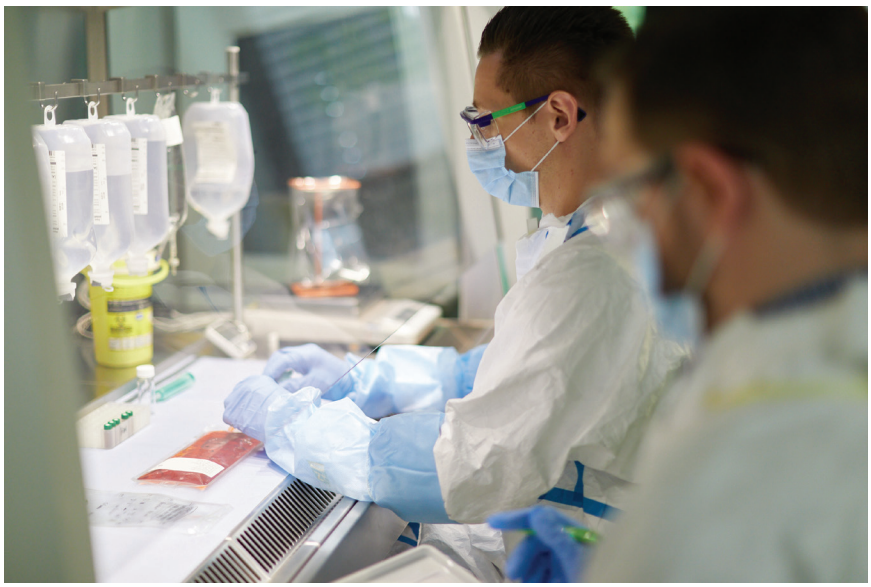

Figure 1.1 Preparation of an anticancer infusion solution. All steps are performed under a safety cabinet with additional filtering systems. Personnel in front of the workbench must wear special protective equipment. Image by Institut für Umwelt & Energie, Technik & Analytik e. V. (IUTA).

for multiparameter methods to screen wastewater treatment plant effluents for up to 100 compounds of interest.

In recent decades, the further development of highly sensitive analytical methods has clearly demonstrated the consequences of the daily use of, for example, pharmaceuticals or household chemicals, but also of industrial chemicals. Almost all types of these organic micropollutants can be detected in the aquatic environment [13]. Pharmaceuticals or household chemicals often enter municipal wastewater treatment plants via human excreta, where they are not removed or are only removed inadequately [14]. Sewage treatment plants are therefore also referred to as point sources of organic micropollutants.

With the amendment of the Urban Wastewater Directive in 2024, large wastewater treatment plants across Europe will have to reduce these micropollutants by 80% in the coming years. This can be achieved through additional treatment stages using oxidative (e.g., ozone [15]) or adsorptive (e.g., activated carbon) processes [16].

With oxidative processes, the potential formation of transformation products, which can be even more toxic than the original substances, must be considered [17]. To reduce these transformation products, the ozonated wastewater is treated biologically according to the current state of the art [16]. However, research based on innovative ozone injection systems has shown that the formation of the carcinogenic transformation product bromate in particular can be significantly reduced [18]. Questions about the additional energy consumption when using oxidative processes for the targeted elimination of micropollutants need to be addressed and answered [14]. However, at a time when wastewater treatment plants are increasingly producing their own electricity from renewable energy sources, the framework conditions for the use of energy-intensive processes are becoming more favorable.

The advantage of activated carbon-based processes is the adsorption of micropollutants on the carbon and the complete removal without the formation of transformation products. Disadvantages, however, are the enormous amount of energy required to produce or reactivate the activated carbon and the much larger space required. In addition to these issues, it is important to ensure that activated carbon loaded with micropollutants does not enter the water, which in some process variants requires additional downstream filtration. Securing a global supply of fresh activated carbon is also important. Increasing demand will inevitably lead to higher prices and supply shortages.

Accordingly, there are several suitable processes for advanced wastewater treatment that must be selected specifically for an individual wastewater treatment plant on a case-by-case basis. A balance between an effective compound removal process and energy efficiency is critical for future sustainable water treatment.

1.1.2.2 Effect-based Analysis for Identifying Relevant Compounds of Interest

Until now, we have been able to quantify small organic molecules “only” with very sensitive instrumental analysis: LC-MS/MS. A common criticism is that although very sophisticated and costly intensive instrumental analysis can detect or quantify a large number of target analytes, no clear conclusion can be drawn about the relevance of the analytical result. For example, the fact that a certain compound

is found in drinking water at a concentration of, say, 100 ng L^{-1} does not mean that it poses a health risk. A chemical may have different effects, depending on its concentration. This is well known in medicine, where a positive effect of a drug is masked by a negative effect when the concentration changes. In addition, the interaction with other chemicals and matrix components plays an important role in the correct assessment of toxic effects [17]. For this reason, the entire community has had to rethink the concept of target analysis, which is based on very sophisticated and expensive instrumental analytical equipment. Effect-based analysis provides a sum parameter and therefore includes all aspects of a sample that contribute to a specific effect. It is therefore complementary to instrumental analysis, and both approaches enable holistic risk management and water quality monitoring [19].

In 2011, we therefore established an S1 laboratory to use genetically modified yeast cells for rapid and cost-effective screening methods for endocrine effects [20]. Instead of first analyzing all samples using LC-MS/MS, we started to use biological screening methods to identify those samples that negatively impact the aquatic environment. To date, the so-called effect-based analysis is not directly linked or coupled to instrumental analysis [21–23]. In addition, effect-based analysis is still an extremely manual process [22]. Most instruments were not designed to be integrated into an automated workflow. Often, these instruments are located in different parts of the laboratory [24]. Things get even more complicated when processes are considered that need to be performed within a very specific time frame. In contrast, LC-MS/MS analysis has been automated since the instruments were first used in routine laboratories. The only manual step is to place the samples in the autosampler of the HPLC system. All other sample measurement steps are fully automated. This may also be the reason why effect-based analysis is not yet a widely used technique.

1.1.3 The Transformation of the Lab: New Concepts for the FutureLab.NRW

1.1.3.1 Instrumental Analysis for Large Molecule Quantification

The idea was to further strengthen the methods and processes we had developed since the beginning of the new millennium, and to combine them with concepts that already existed but were not being used in routine laboratories. To increase our competence in the field of occupational safety, we felt it was necessary to also analyze large molecules, which play a central role in cancer treatment today [25]. In addition to the small molecules used in "conventional" chemotherapy, monoclonal antibodies (mAbs) are a very promising class of drugs that combine all the "positive" properties of small cytostatic drugs, but have no, or at least fewer, negative side effects for the patient. In this context, we have established instrumental analytical methods for the sensitive detection and quantification of mAbs [5,26–28]. Again, the aim was to raise awareness among all healthcare professionals who handle these substances. Although mAbs do not have the same toxic potential as cytostatic drugs, prolonged exposure can lead to sensitization. As there is a high degree of uncertainty about the toxic side effects of mAbs, they are often prepared in specialized pharmacies in accordance with the precautionary principle, as is the case with cytostatics.

1.1.3.2 Direct Coupling of Instrumental and Effect-based Analysis

The next problem we wanted to solve was the lack of hyphenation between instrumental and effect-based analysis. In our FutureLab.NRW concept, we wanted to establish new automation solutions based on flexible automation. As we all know, automation solutions such as those found in the pharmaceutical industry are extremely expensive. The investment is often "fruitful," because in this field of application, we are often dealing with high-throughput applications. On the other hand, a smaller laboratory usually requires various methods that can be flexibly applied to samples of different origins. Highly sophisticated automation systems without the ability to adapt to the method are of no use to these laboratories. This may be an important reason why complete automation solutions have never been fully accepted in a small laboratory. On the other hand, companies that develop instruments for laboratory automation are often very specialized and try to fill the niches that are not covered by larger companies. The general concept of our low-code and no-code programming approach for flexible automation is presented in Chapter 7 by Kjell Kochale.

1.1.3.3 Miniaturization

The next level of our FutureLab.NRW concept is miniaturization. Although there is a strong academic community that has developed and presented numerous approaches, lab-on-a-chip (LoC) technologies have never really made it into routine laboratories. This is mainly due to the lack of robustness and interoperability of LoC systems with instrumental peripherals. In addition, instrumental peripherals are often not considered part of the overall miniaturization strategy. Against this background, the benefits of miniaturization for a routine laboratory are not obvious. The dramatic increase in energy costs, especially for the safe and reliable operation of a laboratory facility, could be an incentive to implement miniaturized systems that take up less space and consume fewer resources (e.g., solvents). Chapter 8 by Tobias Werres provides an overview of some selected cutting-edge research projects currently underway at IUTA using low- and high-cost additive manufacturing as a new and disruptive approach to bring miniaturization into routine laboratories. In Chapter 9, Kerstin Hermuth-Kleinschmidt highlights how the laboratory will be transformed when sustainable, often less energy-dependent processes are implemented.

1.1.3.4 Digitalization

The most challenging task in our FutureLab.NRW was to develop a software platform that can connect all the instruments and software in the laboratory bidirectionally. The goal was to achieve complete digitalization. The idea was not to develop such software in-house, but to combine software that is already commercially available and completely vendor-independent. Vendor here means a company that develops either hardware, software, or both. Section 1.2 explains why we chose a Laboratory Execution System (LES) over a traditional Laboratory Information Management System (LIMS). Max Jochums in then explains some of the intelligent digital workflows we have created using this system.

In short, this is the basic idea behind our FutureLab.NRW concept. A graphical abstract is shown in Figure 1.2. In Section 1.2, we will describe the specifications of this software platform.

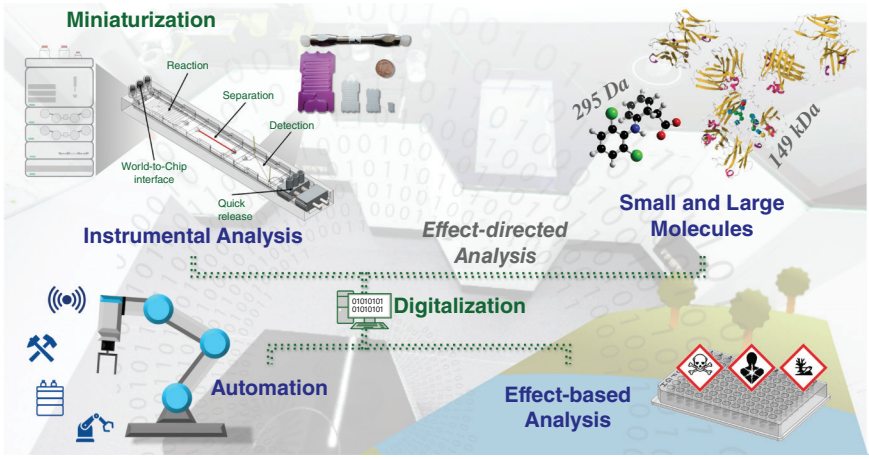

Figure 1.2 Schematic representation of the basic concept of the FutureLab.NRW. At the core, small and large molecules are analyzed using instrumental analytical techniques. Possible biological effects on the aquatic environment are assessed using effect-based analysis. Within the FutureLab.NRW concept, instrumental and effect-based analysis will be linked by the means of flexible automation solutions. To save resources and limit the ecological footprint of the laboratory, all systems need to be miniaturized. The last layer is the digital connection of all software and hardware components. Image by Ricardo Cunha, Institut für Umwelt & Energie, Technik & Analytik e. V. (IUTA)

1.2 Presentation of the FutureLab.NRW Software Platform

1.2.1 Introductory Remarks

The first thing we had to do was decide on what basis we wanted to build the software platform. Our main focus is on research, but we also have an accredited laboratory that works according to DIN EN ISO/IEC 17025:2018. Most routine laboratories have a LIMS, so our first impulse was to get a LIMS. However, after discussing this with many colleagues in our department, we agreed to implement a software platform that would be more flexible. At the end of this process, we defined technical specifications that pointed in the direction of an LES that included an electronic laboratory notebook (ELN) with LIMS functionality.

While a traditional LIMS can also be customized to some extent, the focus is typically more on structured data storage and database management rather than on adaptability. Changing or adding new workflows in a LIMS often requires significant technical support from the vendor. In contrast, the primary focus of an LES is on process orchestration. LES come with their own accessible orchestration environment where new processes can be digitally created and more easily edited. In some cases, they even have built-in orchestration and/or workflow low-code editors, allowing users to create a basic level of orchestration without the need for traditional text-based programming skills. Structured and unstructured data storage is often implemented in separate systems, such as an ELN. Unlike a traditional LIMS, ELN-integrated LES can be customized by the user to a certain extent, which is often required in a research environment. At the same time, they can be configured

to meet the requirements of standards such as DIN EN ISO/IEC 17025:2018. This is the optimal solution for bridging the gap between research and routine laboratories. In Chapter 2, we very briefly outline the key features of an ELN. The chapter also includes two expert interviews on the usefulness of ELNs. The two experts comment on the absolute necessity of using such software tools to make (research) data FAIR (see Section 1.2.3 for a brief definition of this acronym).

Sections 1.2.2 and 1.2.3 define some of the technical specifications of our software platform. For those readers who do not have a strong background in interface and communication standards terminology, some of these details may not be obvious. Therefore, we have included some references in the following chapters and sections, where these terms are described in a general context. We have also illustrated the concept using the workflows created in Chapter 6.

1.2.2 Overall Specifications

To achieve the objectives outlined in Section 1.2.1, the software platform must be seamlessly integrated into the overall laboratory environment. To achieve this, the platform has to be equipped with generic interfaces that allow the connection of analytical instruments and other software systems from a wide range of vendors.

The integration of multi-vendor analytical systems and instruments into the software platform, where technically feasible, is a key requirement. This integration should, as a minimum, allow unidirectional control of the instruments from the software platform, so that analysis parameters can be transferred without manual input. Where possible, the integration should support bidirectional control, allowing the software platform not only to receive analysis parameters from the instruments, but also to send information such as sequence lists and sample lists to the instruments. Chapters 3 and 6 by Mickey Hawelitschek and Max Jochums provide examples of how such digital transformation can be achieved.

Beyond the analytical instruments, the software platform must also facilitate bidirectional integration with a variety of multi-vendor laboratory instruments, including balances, stirrers, hotplates, pH meters, and others. This integration should ideally use technical standards such as Standardization in Lab Automation (SiLA2) or Laboratory Analytical Device Standardization Open Platform Communication Unified Architecture (LADS OPC UA), or alternatively JSON-based REST APIs, where direct compatibility is lacking. Importantly, the platform must also enable the dynamic and results-based transfer of status and measurement data to third-party systems via a programming interface. Finally, the platform must allow for cross-manufacturer upgrades to seamlessly integrate both existing and new laboratory equipment. The reader will learn more about these acronyms in Chapter 4, where Max Jochums briefly outlines the basics of communication protocols, and several experts share their personal thoughts and perspectives on why and how these standards will evolve over the next few years.

In addition to instrument connectivity, the software platform must provide an interface for recording, documenting, and monitoring sensor data, such as temperature from refrigerators and incubators, and flow rate from volume flow controllers. This data must be transferable via WLAN, LAN and/or USB.

The execution of analytical tasks in the laboratory is typically organized in the form of workflows. These are processes consisting of several steps that can be divided into practical activities (e.g., pipetting, weighing, instrumental analysis) and corresponding documentation. To achieve the objectives defined in Section 1.2.1, the software platform must digitize and automate these process steps to a high degree, ensuring that each practical activity is inextricably linked to its documentation counterpart.

1.2.3 Inclusion of the FAIR Data Principles

The overall software architecture should be designed to fully incorporate the FAIR Data Principles [29]. FAIR stands for "Findable, Accessible, Interoperable, and Reusable." The first principle (Findability) means that research data should be easy to find, for example, by providing an accurate description and metadata. The second principle (Accessibility) refers to the fact that research data should be open and freely available for use by the scientific community. The third principle (Interoperability) states that research data should be standardized and machine-readable to allow easy integration with other data sources and systems. The fourth principle (Reusability) emphasizes the importance of clear and open licenses and the use of standards to ensure that data can be reused. In summary, the FAIR Data Principles are about designing and delivering research data so that it can be easily found, used, linked, and reused to advance scientific knowledge.

1.3 The Center for Life Science Automation (CELISCA) – An Interview with Prof. Dr. Kerstin Thurow from the University of Rostock

1.3.1 Personal Introduction

Dear Kerstin, you were the youngest female professor in Germany, and you began your habilitation as a chemist. You have also adopted the principle of the cross-disciplinary collaboration. Could you briefly explain your motivation for focusing on automation solutions for the life sciences?

Thank you for the reminder of my beginnings in laboratory automation, which is now almost 25 years ago. I originally studied chemistry and then did my doctorate in organometallic chemistry at the Ludwig-Maximilian-University in Munich. After completing my PhD, I initially decided on a postdoctoral position in Rostock at the Institute for Automation Technology to pursue my second hobby, analytical measurement technology, especially mass spectrometry. Here I completed my habilitation on measurement concepts for the determination of organo-arsenic warfare agents (1999). In Rostock I worked together with an electrical engineer who was already at this time working on the digitization of the mass spectrometer on which I had carried out numerous measurements. And so the idea came about: Why not automate laboratories and laboratory processes? At that time, chemical syntheses

and analytical procedures were still entirely manual work. Automation would have been a massive step forward here. Luckily, I had superiors who may have internally smiled at the idea of automating laboratories, but they let me do it and encouraged and challenged me. This is how the first automation solution was created for a project in the area of investigating warfare agent contamination in soil. The automation system was able to weigh samples, add solvents, and perform filtrations. Since we were working with toxic samples, this was a big step forward for safer working conditions. This was a start, but it became clear that the need or, let us say, the wishes of potential customers in this direction were not yet really there. Rather, developments could be seen in the pharmaceutical industry; high-throughput screening procedures developed over time. These new solutions were mainly available to financially strong large industries; smaller companies could not benefit from them. Thus, we developed the idea of establishing a globally recognized academic research center that conducts research in the field of Life Science Automation so that solutions are actually available to a wide variety of potential users. We were then able to convince the Federal Ministry of Education and Research (BMBF) with our concept, from which we received good financing over several years for the implementation of our ideas and the establishment of CELISCA – the Center for Life Science Automation.

It is usually said that everything in Mecklenburg happens 100 years later. But occasionally we are also pioneers, for example, when the University of Rostock established the world's first chair for laboratory automation in 1999. I was able to convince the selection committee with my concept. In 2004, I was appointed a full professorship Automation Technology/Life Science Automation.

The portfolio of applications in our research has now expanded significantly. Classic life science applications are still in the focus, but these increasingly involve the handling of individual samples and the automation of highly complex processes. In addition, there are also processes in material sciences or quality control in different industrial laboratories, which bring new challenges. Due to our very modular approach, such an expansion of the portfolio can be achieved. Shortly I can say: we want to make laboratory work more efficient and safer, no matter what the specific applications are.

1.3.2 CELISCA's Approach to Automation

Automation has a long tradition in the life sciences. There are many companies offering automation solutions to the, for example, pharmaceutical industry. What approach have you followed during your scientific career?

When we started working in the field of laboratory automation, the situation was entirely different from today. Laboratory automation was only just beginning to develop in the late nineties. Driven by the requirements and wishes of the pharmaceutical industry in the field of drug development, solutions in the field of laboratory automation slowly developed – primarily in the pharmaceutical companies themselves or with special proprietary contracts of automation companies. We entered this field at the end of the 1990s and dedicated ourselves to

the automation of processes in the life sciences. The aim was to really build up research and development in this area in the academic sector. Our approach was to focus on flexible, modular systems that can be used for a wide variety of processes with certain application-specific adaptations. Proprietary solutions are, of course, often easier to implement and are justified in certain applications. But only through a high degree of modularity it is possible to provide affordable solutions for everyone, including small- and medium-sized companies and research institutions. This modularity naturally also means that one has to think extensively about system concepts and the systematization of different conceptional approaches, and describe them in a way that is generally applicable. We have done this extensively; many researchers and users now use these concepts when it comes to their automation projects. We not only differentiate between partial and full automation, but also between closed (proprietary) and open (flexible) systems, or centralized and decentralized systems.

Another point is that we have never had a me-too policy in our research and developments. Systems that are already available and established on the market are not a subject of research for us. We concentrate on devices, system components, and systems that are not available on the market and develop solutions for them. Thus, you can say that we are looking to find the niches in this big area of laboratory automation.

Even if we are working in the research field, our developments should ultimately lead to prototypes and products that can then be marketed. We therefore only partially support a completely open-source approach, as favored by some academic representatives.

1.3.3 Mobile Robots in the Lab

It may sound like science fiction to many researchers and lab technicians when they are told that there are mobile robots that can navigate autonomously and freely around the lab or even an entire building. The reality is different. Many laboratories do not even consider using mobile robots for various reasons. What do you think about the general use of this technology, and which sectors will be the first to implement mobile robots on a large scale?

Mobile robots are, of course, something very fascinating; they are still some kind of science fiction. However, since many laboratories today have not even automated their actual laboratory processes, the use of mobile robots has so far received little attention. Mobile robots in the laboratory do have several potential advantages. They can very well take on routine tasks, such as transporting samples and labware, especially in distributed laboratory environments. This allows human employees to concentrate on more complex and creative tasks. Mobile robots enable an extension of operating hours and can therefore make a significant contribution to increasing productivity and efficiency. They can also reduce human errors and ensure that samples and data are handled consistently and precisely. This is particularly important in clinical laboratories. Mobile robots also have great advantages in terms of safety in laboratory environments, as they can continuously monitor environmental

conditions, the status of equipment, and the progress of experiments and provide data and alarms in real time in the event of deviations or problems.

All of these advantages, however, are offset by some challenges. The high purchase, installation, and maintenance expenses of mobile robots can be prohibitive, especially for smaller laboratories or research laboratories. The goal here must be to create more cost-effective solutions. This has already worked with the transition from industrial robots to lightweight robots, which, with the establishment of cost-effective so-called cobots, has led to a sharp increase in the proportion of robots in laboratories. A similar development can be expected in the future in the field of mobile robots, too.

Even if users find mobile robots fascinating, they do not really trust them in terms of reliability and performance. This is also because, although there are some providers on the market, the applications have so far only been partially convincing. The vast majority of providers use the principle of placing a classic robot arm on a mobile platform. The mobile robot arm takes over the samples or labware at the starting and destination locations. This requires high levels of precision to achieve error-free pick-and-place. Due to the technically lower accuracy of the mobile platforms, additional solutions must be implemented, such as barcode or QR code identification or camera-based optical recognition. This adds additional complexity to the systems and thus also increases potential failure rates. Thus, users are still very reluctant. We are pursuing a different approach with our mobile robots. The mobile robot is merely a transport instrument; the samples are transported on a tray that can hold up to nine racks in microtiter plate format. The trays are picked up and placed at transfer stations; special mechanical parts ensure the precise positioning. That means that the high levels of precision are not required, as in the first case. The samples are then fed to the actual stations via interface robots; these are already present in many automated processes. The technical complexity is considerably lower, and the reliability is very high.

There are also newer approaches that, among other things, provide for individual devices to be placed on mobile platforms and then flexibly assembled depending on the workflow. This concept is very exciting, but here too the question of positioning accuracy remains. In addition, the question arises as to the extent to which the permanent transport of devices regarding calibrations, etc., is actually realistic and whether there are actually applications in the laboratory.

A challenge that should not be underestimated is the integration of mobile robots into existing LIMS and devices. This integration can be technically very demanding and requires significant adjustments. Thus, suitable workflow management systems are necessary, which must be highly flexible. There are currently only a limited number of such systems available on the market; existing systems again involve high investment and maintenance expenses.

When establishing mobile robots in the laboratory, the first to take up the role will be industries that have an immediate need for efficiency, accuracy, and safety, as well as the use of existing resources. This will be the case primarily in pharmaceutical and clinical laboratories. However, as the technology matures and becomes more accessible, it is expected to become more widely accepted and used in various laboratory environments.

1.3.4 The Limits of Automation

What do you see as the ultimate limits of automation? There is the specter of people losing their jobs and being replaced by autonomous robots. Do you agree with this "vision"?

The question of the reduction of jobs through increasing automation is a controversial issue. If we look back at history, we can see that these fears have existed in all eras of industrialization. Just think of the Luddites, people who at the beginning of the nineteenth century, turned against the introduction of new machines in the textile industry in England. Another example is the Silesian weavers' revolts.

It is difficult to make a general statement about the destruction of workplaces by automation, and I would not support it. Classic studies assume that jobs could be destroyed, particularly in the manufacturing industry. However, automation also creates numerous new jobs, since robots and automation systems ultimately have to be designed, operated, and maintained. A study by the Institute for the Future of Work has shown that in the first decade of the twenty-first century, 1.5 million additional jobs were created through automation in Europe alone.

It is clear that low-skilled jobs will increasingly be affected by automation; human labor will be replaced here. The aim here is to train the people who lose their jobs accordingly so that they can either work in the new automated jobs or take on alternative work. There is one thing that machines cannot do but humans can: human attention, communication, and empathy. In this area, we have a massive shortage of staff that could be solved by educating people who are losing their jobs due to increased automation.

If we look at the laboratory sector, however, these problems with low-skilled staff generally do not exist there. Laboratory technicians are very well trained and often have extensive specialized knowledge. Here, we are more likely to have the issue of a growing shortage of skilled workers. We will have difficulty fulfilling our laboratory tasks at all in the future, not to mention increasing requirements and sample numbers. Existing knowledge cannot be passed on and disappears. Here, automation offers a good opportunity to relieve and support existing staff, increase sample numbers, and "preserve" specialist knowledge.

Ultimately, scientific and technological progress cannot be stopped. We cannot (and do not want to) stop it. Rather, we must develop strategies for how we want to deal with the social changes resulting from automation. Automation can certainly give us a lot of new freedom. We must use this, including to master the negative consequences of automation.

What are the limits of automation today? As an engineer, I would say we can automate any process. It is, of course, a question of cost; the more complex and complicated a process and thus the required automation solution, the higher the costs. A major problem is the complexity and variability of experiments. Many scientific experiments require adjustments and creative solutions that are difficult to automate. Specific research questions, in particular, often require tailor-made approaches that cannot be covered by standardized automated systems. Automated systems are also typically less flexible and adaptable than human laboratory technicians, especially

when unexpected issues or new tasks arise. This is definitely where automation has its limits. The integration of different automation systems and software solutions can be very complex and time-consuming. There are still no generally applicable standards, such as those in the field of computer technology. Handling and analyzing the large amounts of data generated by automated systems can also be challenging. Despite advanced technologies, human knowledge and experience remain essential, especially for interpreting complex data and developing new hypotheses. Scientific research thrives on creative ideas and intuitive approaches that are difficult to replicate using machines.

The limits of automation are always related to the current state of science and technology and are therefore constantly changing.

1.3.5 The Future of Training

Since we are obviously not going to be replaced by robots in the foreseeable future, there is a strong need to reform education. What do you think needs to be done to significantly improve the interdisciplinary education?

A whole book could certainly be written on this question. Let me try to briefly formulate some thoughts on this.

To improve interdisciplinary education and meet the future demands of the labor market, several reforms in education should be considered. A significant aspect of this is the integration of interdisciplinary projects. Schools and universities should promote projects that combine several disciplines. For example, science, technology, engineering, and mathematics subjects could be integrated to show students how the findings of individual subjects can be combined to form a bigger picture. This requires appropriate training and development of teachers to learn about new interdisciplinary approaches and pedagogical methods and to integrate them into their teaching.

Teamwork and collaborative learning should be promoted more. Interdisciplinary education often requires collaboration between students from different disciplines. Educational institutions should offer courses and projects that emphasize teamwork and collaborative learning to help students work effectively in interdisciplinary teams.

Our sometimes very school-like study plans should be adapted and offer the possibility of greater flexibility to enable students to take courses from different disciplines. This could be achieved, among other things, by introducing more interdisciplinary modules.

A major shortcoming of our education is that the theoretical parts of the teaching are typically not matched by the practical parts. Practical learning through internships, studies, and projects with real companies can help students put their theoretical knowledge into practice while integrating different disciplines. Courses that promote critical thinking and problem-solving skills should also have a permanent place in the curriculum.

This, of course, assumes that universities and technical colleges have the necessary personnel capacity to implement such things – since they are time-consuming.

I see another possibility in the establishment of interdisciplinary research centers, which are increasingly being created. We established CELISCA in 2003 precisely for the purpose of bringing researchers and students from different departments together to work on joint research projects.

The rapid changes in technological development are making continuing professional development and lifelong learning increasingly important. Educational institutions should offer related programs that enable professionals to expand their knowledge in various disciplines and adapt to the changing demands of the labor market. However, this also means that educational institutions must have the appropriate personnel and material resources to carry out these time- and personnel-intensive tasks.

In addition to technical knowledge, soft skills such as communication, teamwork, emotional intelligence, and adaptability should also be promoted, as these skills are particularly important in interdisciplinary teams.

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