Three Studies of Shared Digital Labs:
The Role of Trust in Business and Maturity Model Development

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
May 7, 2022

Keywords: Sharing economy, Technology-based trust, Platform business model,
Digital transformation, Maturity measurement, Online labs

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Abstract (EN)

Laboratories (labs) complement theoretical teaching/learning content in STEM subjects to promote understanding with practical knowledge and experience. However, these labs are typically expensive and available only to local user groups, so not every university can offer the same or equivalent labs. In addition, many universities are not well prepared to share labs with other institutions or to use labs from other institutions. Based on information and communication technologies and the concept of the sharing economy, online labs form the basis for digital exchange in networks. In addition to technical and didactical considerations for the use of online labs, organizational considerations for sharing lab are becoming increasingly important.

This dissertation addresses organizational problems of sharing digital online labs for STEM subjects. Sharing of online labs is currently insufficient. In fact, many research projects on online labs fail to continue to operate these labs in a way that covers costs after research funding ends. This work covers three studies to promote sustainable use of shared online labs. The three studies address the following issues. (1) A platform business model that promotes sustainability by enabling online lab sharing, with defined success criteria and functional requirements validated through industry comparisons, stakeholder interviews, and surveys. (2) A systems view of trust as a key element for platform business to identify gaps and opportunities for research and practice. (3) A maturity model to determine the effectiveness of digital lab transformation, assessed through expert workshops and expert interviews.

Abstract (DE)

Labore ergänzen theoretische Lehr-/Lerninhalte in MINT-Fächern, um das Verständnis mit praktischen Kenntnissen und Erfahrungen zu fördern. Diese Labore sind jedoch in der Regel teuer und stehen nur lokalen Nutzergruppen zur Verfügung, so dass nicht jede Universität gleiche oder gleichwertige Labore anbieten kann. Darüber hinaus sind viele Universitäten nicht gut darauf vorbereitet, Labore mit anderen Institutionen zu teilen oder Labore anderer Institutionen zu nutzen. Online-Labore bilden auf Grundlage von Informations- und Kommunikationstechnologien und dem Konzept der Sharing Economy die Basis für die gemeinsame Nutzung in digitalisierten Netzwerken. Neben technischen und didaktischen Überlegungen zur Nutzung von Online-Laboren werden organisatorische Überlegungen zum Teilen der Laborinfrastrukturen immer wichtiger.

Diese Dissertation befasst sich mit organisatorischen Problemen der gemeinsamen Nutzung digitaler Online-Labore für MINT-Fächer. Die gemeinsame Nutzung von Online-Laboratoren ist derzeit unzureichend. Tatsächlich gelingt es vielen Forschungsprojekten zu Online-Laboren nicht, diese Labore nach Abschluss einer eventuellen Forschungsförderung kostendeckend weiterzuführen. Diese Arbeit behandelt drei Studien zur Förderung der nachhaltigen Nutzung gemeinsam genutzter Online-Labore. Die drei Studien befassen sich mit folgenden Themen. (1) Ein Plattformgeschäftsmodell, das die Nachhaltigkeit fördert, indem es die gemeinsame Nutzung von Online-Laboren erleichtert. Die Validierung erfolgt anhand definierter Erfolgskriterien und funktionaler Anforderungen, die durch Branchenvergleiche, Befragungen von Interessengruppen und Umfragen ermittelt wurden. (2) Eine Systembetrachtung des Vertrauens als Schlüsselelement für das Plattformgeschäft, um Lücken und Chancen für Forschung und Praxis zu ermitteln. (3) Ein Reifegradmodell zur Bestimmung der Effektivität der Transformation digitaler Labore, bewertet durch Expertenworkshops und Experteninterviews.

Acknowledgments

For my wife. Thank you for all your support over the years.

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Chapter 1

1 Introduction

Science, technology, engineering, and mathematics (STEM) education requires applied tasks and problems to promote conceptual understanding, practical knowledge and experience (Feisel & Rosa, 2013). Laboratories (labs) provide students with a special hands-on engineering experience and allow them to explore systems and their real-world behavior in a protected environment (Zutin et al., 2010). However, for universities, these specialized labs involve high investment and operating costs, their utilization is often low, access is limited to local user groups (students and researchers), and the labs are subject to rapid loss of innovation (Heradio et al., 2016). In addition, funding for the labs is solely dependent on budgetary resources and grants and is therefore subject to corresponding funding fluctuations.

Digitalization technologies can be used to transform traditional labs, making them available online, allowing access to labs across locations, eliminating the need for in-person lab attendance, and thus enabling the delivery of lab experiences via distance learning (Mani & Patvardhan, 2006). These online labs are experiments supported by information and communication technologies (ICT) in which manual efforts are eliminated and can be accessed via the Internet (Zutin et al., 2010). According to Zutin et al. (2010), online labs are divided into software simulations (or virtual labs) and labs with real hardware equipment (or remote labs), through which these achieve advantages in availability, observability, accessibility, and security (Heradio et al., 2016). Expanded availability, where users can access online labs from anywhere and at any time, offers universities wide-ranging opportunities to increase usage through new business areas of the transformed labs, as they can be used outside of class hours (Gardel et al., 2012).

By making labs available online, they can be shared with other institutions and users, opening up a new area of business and thus a potential permanent source of revenue. The sharing economy describes behavior that encourages the sharing of resources to benefit from increased resource utilization, cost advantages, and access to new knowledge (Goudin, 2016). The digital transformation of labs to online labs makes them good candidates for the sharing economy, which means that additional users can be reached. The biggest challenge in sharing is mutual trust (Gossen et al., 2019). The user must trust that the lab will be available at the right time in the expected condition, while the operator trusts that the lab will be used correctly and under the agreed conditions and that no damage will occur. For online assets such as online labs, the parties involved may not know each other and must have confidence that each other's requirements will be met. Independent third-party providers offer indication to this and help to build initial trust before own experience can be gained (Ba et al., 2003). For online labs, a maturity model helps to be a kind of indication of a third party that describes how effective the lab's digital transformation is. If a lab has a high maturity level, a user should be more confident that the lab meets the requirements of digital transformation. Thus, for this dissertation entitled *Three Studies of Shared Digital Labs - The Role of Trust in Business and Maturity Model Development*, the following approach was developed. (1) A platform business model for activating online lab sharing, (2) considerations for building initial and long-term trust between actors as a critical challenge of a lab sharing platform, and (3) a maturity model for capturing organizational transformation of online labs to build trust among platform stakeholders.

(1) A platform business model that promotes lab sharing. Sharing is originally a private matter, but new concepts for sharing goods and services between individuals and companies are emerging worldwide (Beutin, 2018). Sharing is now taking on far-reaching new forms, such as car sharing, code sharing, file sharing or food sharing, and is conquering new business areas with innovative business models. The underlying concept of the sharing economy describes behavior in which either individuals or organizations seek to share existing resources such as human, tangible, and intangible resources (Goudin, 2016). At first glance, the sharing economy for digital labs offers benefits to providers through increased utilization, and the customer gains access to a greater supply of labs. According to Eikaas et al. (2003), a major obstacle to a sustainable business model is "*the willingness of customers to buy access to laboratory resources*". The benefits of sharing must be demonstrated over direct access, and the real benefits are the selling point. Customers expect valuable content, ease of use, affordable services, access to otherwise inaccessible materials and equipment, and customer support. In addition, sharing must be trustworthy. This point relates to both the functional and success criteria of sharing. Compared to physical markets, where trust is built through relationships, the digital environment currently uses transparent rating systems that consider the quality and reliability of the actors (Schallmo et al., 2017). Nevertheless, this does not achieve the interpersonal trust that comes into play in social contacts. This problem will be further explored in the next section. However, a closer look at potential user groups such as industry and students also shows that they may have different

requirements. Thus, a business model for online labs is needed that is tailored to the needs of customers and providers while fulfilling the trust in network organizations. Following the business models of the leading providers in the sharing economy, a multi-sided platform would be suitable for activation of the concept. A multi-sided platform is an intermediary for exchanging value between interested parties and providers from two or more markets (Zhao et al., 2019); for example, it is used by Airbnb (landlords and renters), eBay (buyers and sellers), and Facebook (users, advertisers, and content developers). In the lab sharing concept, the universities would offer various online labs, and students could meet their needs via a corresponding platform. Here, the interested parties are the students and the providers are the universities. The marketplace is the sharing platform where the joint exchange and coordination service takes place and supports matching of providers and buyers (European Commission, 2013). The main difference with a traditional business model is that the marketplace does not acquire ownership of the traded resource and therefore has no influence on the way it is presented or the price. The provider and the buyer therefore directly control the terms of sharing. The online lab provider must therefore keep its offer and prices attractive to attract and retain buyers. More users on both sides (supply and demand) increase the benefits of the marketplace, the so-called network effect (Abdelkafi et al., 2019). The challenges of a multi-sided platform, according to Henseling et al. (2018), are: (1) building user trust, (2) evolving the marketplace offering, and (3) attracting new user groups. Trust is extremely important for the development of the online lab, as a loss of trust could lead to the collapse of the network effect. In the example of lab sharing, the user must trust that the online lab will be available at the right time and in the expected condition, while the operator, e.g., the university, trusts that the lab will be used correctly and under the agreed upon conditions and that no damage will occur. Particularly with online resources such as online labs, the parties involved may not know each other and must have confidence that each other's requirements will be met. Independent information from third parties can provide clues to this and help to build initial trust before one’s own experience can be gained (Ba et al., 2003).

This business model starting point led to two other organizational aspects for the shared digital labs. First, trust to leverage the business model that builds, initially but also in the long-term, trust between provider and customer, to avoid disruptions in the network. Second, a maturity model that allows providers to pre-evaluate the effectiveness of the online lab's transformation, and that provides a kind of trust reference for the user of a third actor that evaluates the effectiveness of the online lab's organizational transformation.

(2) Trust to leverage the lab sharing business model and increase organizational efficiency. In general, trust arises from and in relationships, therefore it can be created and destroyed (Flores & Solomon, 1998). A trust relationship involves two parties, there is uncertainty and risk, and the trust giver relies on the honesty and goodwill of the trust taker (Siau & Shen, 2003). A distinction is made between weak and strong trust relationships, with a strong relationship characterized by feeling secure and trusting that our partner can rely on us and will respond to our needs (Rempel et al., 2001). Trust occurs in various social contexts and can arise both between individuals and between individuals and organizations as a hybrid form (Zaheer et al., 1998). A further distinction is made between trust that already arises on the basis of an existing trust relationship and trust that must first be established. In addition to initial trust, there are trust models that reflect the development of trust during the interaction of the parties, such as that of Lewicki and Bunker (1996). Their transitional stages of trust development model describe how two parties form and develop a new relationship and explains how trust and relationships change, develop, or decline over time and how trust can be restored. In doing so, the transitional stages of trust model maps different benefits and different costs for each stage as a sequential iteration (Lewicki & Bunker, 1996).

In contrast to trust in social context, online trust or technology-based trust is increasingly being studied, e.g., in e-commerce (Gefen, 2000), in smart personal assistants (Zierau et al., 2020), in blockchain platforms (Zavolokina et al., 2020), or for entire research disciplines such as information systems (Söllner et al., 2016). The difference with online trust is that in an online situation, it is more difficult to reasonably assess the potential harm and good will of others (Friedman et al., 2000). To this end, new methods have been developed, such as a user-centered rating system, trusted third party certifications, or trusted third party recommendations. Long-term trust conditions have not yet been used in technology practice because the focus to date has been on initial trust rather than the impact of long-term development. Similar to Lewicki and Bunker's (1996) model, Williamson's (1993) transaction cost theory follows a parallel idea when parties begin to validate activities in terms of trust to build a knowledge base about their needs, preferences, and priorities. According to this theory, a transaction can be processed and organized more or less efficiently, which describes the transaction costs. An adaptation of this transaction concept for trust in a technology context could map trust interactions into a trust level model and promote benevolent behavior through lower (transaction) costs. Thus, a user with a higher trust level would be more willing to accept a trusted online lab offer because the expected transaction costs are lower. In addition, a lab provider would be more willing to share its lab if the user is trustworthy. One way to provide information to users to build long-term trust is to develop a technology maturity model, as described in the next section, enabled by a business model in which costs are influenced by trust levels. The combination of a business model and a maturity model, both of which promote long-term trust, should ensure that after the initial trust, there is stakeholder interest in building a long-term trust relationship, thus underpinning the sharing.

(3) Maturity model to demonstrate the effectiveness of digital lab transformation. Digital transformation is defined by Pousttchi et al. (2019) as a change process that companies undergo due to the emergence of new technologies and their social and economic impact. Digital transformation of labs is therefore defined as a continuous development process that goes beyond the emergence of new technologies and their social and economic impact to include the construction of a new business ecosystem. Various studies measure this transformation from a didactic and technical perspective in order to make its effectiveness transparent to stakeholders and to build trust. The pedagogical effectiveness of online labs at different stages of digital transformation as an indicator of the usefulness of an experiment to achieve the desired goal has been studied by various authors, e.g., Brinson (2015). Similarly, studies on technological effectiveness, such as the design, development, and implementation of different digital lab transformations have been pursued, as by Prada et al. (2015). Corresponding maturity models for both areas can also be found in the literature (Abbas, 2019), but a model that takes into account organizational change towards sharing between institutions and thus the needs of users and operators is currently missing. The organizational effectiveness of digital lab transformation has not been further researched since then but is gaining importance over time due to the changing requirements of lab sharing, such as building initial trust between different actors and organizations. Numerous international research projects involving online labs have failed to continue the developed environments after the project funding phase (Esposito et al., 2021), not least due to lack of organizational effectiveness.

Digital lab transformation effectiveness is defined as the evaluation of the lab's digital transformation efforts with the goal of sharing (Kuntsman & Arenkov, 2019). In this study, effectiveness is specifically defined as the quality of the change process organizations undergo that involves technology and its social and economic impact. Specifically, effectiveness is about four dimensions: (1) universality and accessibility, (2) user management, (3) scalability and extensibility, and (4) learning support. These are aligned with Garcá-Zubía's (2021) structures for the requirements of a remote lab management system and the characteristics of a remote experiment. Universality and accessibility describes if and how a lab is accessible to the user in any technological scenario and refers to the original design of the experiment (García-Zubía, 2021). Preliminary research has shown that trust factors are reflected here. For example, Orduna et al. (Orduna et al., 2016) shows that it is not possible to access labs of others if there is no reliable trust mechanism. The second requirement, user management, describes how users gain access to online labs, how their data is managed, what user rights they have, and how their experiment dataset is stored (García-Zubía, 2021; Ying & Zhu, 2004). Scalability and extensibility describe how easy it is to adapt the labs to new audiences, expand them to include more experiments, extend them to more facilities, certify the results, and ensure sustainability (García-Zubía, 2021). The fourth requirement is learning support or pedagogical effectiveness, i.e., whether and to what extent the online lab supports coursework (García-Zubía, 2021). The lab should support not only experimentation, but also social coordination, the lab environment, and individual differences (Nickerson et al., 2007). For an application in a lab-sharing concept, it should therefore be further investigated whether the effectiveness of digital lab transformation in support of the sharing economy can be mapped in a maturity model. The practical benefit for the marketplace promises (trust) comparability of the effectiveness of shared labs, both from the provider perspective in terms of administrability, financial and personnel effort, and from the demand perspective in terms of learning success.

This leads to the **research questions** addressed in this dissertation:

- **Paper 1**: What are the success criteria for a sustainable business model of digital labs? And what are the functional requirements of a multi-sided platform for digital labs?
- **Paper 2**: How is trust in technology and in the use of technology created, maintained, destroyed, and possibly rebuilt?

- **Paper 3**: Can the effectiveness of digital lab transformation be adequately described in a maturity model (MM) and thus used as a tool to support the sharing economy?

Together these three papers also consider the following research question: **How can a successful business model be developed for shared digital lab spaces?**

Figure 1 describes the structure of the dissertation, which is divided into the introduction, the three cumulative related papers, and a conclusion. The introduction describes the central problems of the three studies on shared digital labs and their interplay for a sustainable online lab sharing. The first paper on business models addresses the problem that labs are associated with high investment costs, utilization is often low, access is limited to local user groups, labs are subject to a rapid loss of innovation, and financing is exclusively dependent on budget and funding and thus subject to corresponding fluctuations. Classic business models do not seem to work, so the question arises as to what success criteria and functional requirements should be placed on digital labs? The second paper describes trust as a success criterion for the business model in more detail. Trust is considered a core element for sharing digital assets such as online labs (Gossen et al., 2019). How technology-based initial and long-term trust development can be built is explored. Building on this, the paper elaborates why this is a core element for the sustainability of the sharing business model and how initial and long-term trust can be leveraged for sharing labs. The third paper emphasizes that the effectiveness of the lab's digital transformation should be made transparent to the user and the platform operator, as has been shown many times for both didactic and technical transformation (Heradio et al., 2016). This ought to be used by lab operators for design, implementation, or improvement and by users and students alike for comparability to build trust. In the conclusion of the dissertation, the results and the contribution to literature and practice are elaborated and open challenges and a possible way forward for share lab networks are presented. Finally, the generalizations and limitations of the dissertation are described.

Figure 1: Structure of Dissertation

Ch.1: Introduction	• How can a successful business model be developed for shared digital lab spaces?					
Ch.2: Paper 1	• What are the success criteria for a sustainable business model of digital labs? • What are the functional requirements of a multi-sided platform for digital labs?					
Introduction	Research Methodology	Literature Review	Multi-Sided Platform for Digital Labs	Evaluation	Discussion	Conclusion and Outlook
Ch.3: Paper 2	• How is trust in technology and in the use of technology created, maintained, destroyed, and possibly rebuilt?					
Introduction	Interpersonal Trust	Trust Studies Involving Technology	Discussion of the Issue	Conclusion		
Ch.4: Paper 3	• Can the effectiveness of digital lab transformation be adequately described in a maturity model (MM) and thus used as a tool to support the sharing economy?					
Introduction	Theoretical Background	Methodology	Expert Workshop to Develop the MM Concept	Expert Interviews to Refine the MM	Discussion and Contribution	Conclusion and Future Work
Ch.5: Dissertation Conclusions						

It should be noted that individual aspects of this dissertation have already been published; an overview of the articles can be found in Appendix A.

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Chapter 2

2 Paper 1: A Multi-Sided Platform to Activate the Sharing of Digital Labs

https://doi.org/10.3991/ijoe.v17i11.25183

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Abstract: This paper presents a business model for digital laboratories (labs) to promote sharing in network organizations. Using information systems design science research methodology, a multi-sided platform is created and evaluated as a sustainable business model. Digital labs complement theoretical concepts in science, technology, engineering, and mathematics (STEM) to promote understanding of concepts, practical knowledge, and experiences. However, these labs are expensive and typically only available to local user groups, and not every university can offer the same or equivalent labs. Many universities are not well prepared to share labs with other institutions or to be part of a network organization. Among the findings are that digital labs are becoming more important, that there is an emerging trend from product- to service-oriented solutions, that a lab-sharing marketplace should provide targeted offerings for teaching and training, and that industry customers and students are showing interest in digital labs education content. The willingness to pay for students and industry is there, but for students the discussion remains ethical in nature as to who should pay for education. On the other hand, industry customers point out that there is a fear of losing intellectual property and security risks. This paper shows how a sustainable business model for digital labs activates lab sharing. Then universities can offer a better curriculum, instructors have more opportunities to provide a good education, and only then can students have access to more lab environments.

Keywords: Business model, Sharing economy, Digital laboratory, Multi-sided platform, STEM education

2.1 Introduction

New concepts for sharing goods and services between individuals and companies are emerging worldwide (Beutin, 2018). Well-known examples, such as Uber and Airbnb, are seizing new business areas with innovative business models. The sharing economy concept, which was introduced by Weitzman (1984), describes behavior where either individuals or organizations make an effort to share existing resources. These include human, material, and non-material resources (Goudin, 2016). Thus, the sharing economy benefits in the form of higher utilization of resources, cost advantages, and access to new knowledge (Goudin, 2016). Boons and Bocken (2018) categorized the expectations of the sharing economy into ecological sustainability, labor conditions, customer value, social relations, justice, competitiveness, and profitability. In an academic environment, there is great potential to share resources using the sharing economy concept and digitalization technology (Schmid et al., 2018). Experiments in lab environments with different specializations play an important role in the education of future engineers and scientists (Pfeiffer & Uckelmann, 2019). In science, technology, engineering, and mathematics (STEM), the handling of tools, actors, sensors, machines, and robots are taught and learned in labs (Upadhya et al., 2019). Physical labs are used to provide students with hands-on experience and professional techniques and practices. They allow the manipulation of physical components to better understand their constraints in a safe environment. Therefore, universities have their own cost-intensive lab infrastructures with individual learning goals. Unfortunately, labs often have a low utilization rate. This makes labs used for educational purposes good candidates for implementing the concepts of shared knowledge, shared infrastructure, and shared facilities by applying digitalization technology. Therefore, conventional labs are virtualized or made remotely accessible by means of various digitalization technologies. Personal presence in on-site labs is not required, as access is possible via the Internet. Thus, labs can be offered to different user groups. However, there are different solutions for digitalizing real labs to create a shared lab infrastructure (García-Zubía & Alves, 2011; Romagnoli et al., 2020). The benefits for users include (1) availability: users have access to new resources and digital labs can be used from anywhere at any time, (2) accessibility for disabled people, (3) observability: experiments can be watched by many people, and (4) safety: digital labs can be an alternative to hands-on labs for dangerous experimentation (Eikaas et al., 2003; Heradio et al., 2016; Tawfik et al., 2014). In light of the Covid-19 pandemic, access to lab resources via the Internet is becoming increasingly important. Students are not exposed to danger but can still access learning resources. At first glance, the sharing economy for digital labs offers advantages for suppliers through higher capacity utilization, and the customer side gains access to a wider range of labs.

According to Eikaas et al. (2003), a main obstacle for a sustainable business model is *"the customers' willingness to buy access to laboratory resources"*. From a market cost point of view, the question of under what conditions customers prefer to rent labs rather than build them themselves arises. Another question relates to at what point customers would rather form a network with other institutions to gain access to labs. Coase (1937) investigated why every needed resource is not purchased through the market using the price mechanism. The reason is the corresponding high costs of organizing and the so-called transaction costs, such as searching costs, contracting costs, and coordination costs (Amit & Zott, 2001; Coase, 1937). Consequently, the use of market costs and the forming of an organization has economic benefits. The entrepreneur has to perform the function cheaper than the market transactions he is replacing (Coase, 1937). The relevance and effect of transaction cost economics were highlighted by three Nobel Prize winners, Ronald Coase (Nobel Memorial Prize in Economic Sciences in 1991) and Oliver Williamson and Elinor Ostrom (Nobel Memorial Prize in Economic Sciences in 2009). With lower transaction costs, it is recommended that labs should be sourced from the market. Today, the Internet and communication technologies are changing the dynamics of transaction costs (Tapscott et al., 2000). As a result, many transaction costs have been significantly reduced and sometimes approach zero (Abdelkafi et al., 2019; Tapscott et al., 2000). This justifies the change from traditionally isolated firms to new forms of networked organizations. The costs of cooperation and integration with partners (e.g., outsourcing) and customers in business processes (e.g., customization, customer services) are no longer inaccessible (Osterwalder, 2004). Williamson (1987) states that even reputation, trust, and transactional experience can lower the cost of exchanges. Markets have also been revolutionized by the increasing frequency of transactions, the reduction of transaction uncertainty, the reduction of asset specificity, and the large number of interacting parties (Amit & Zott, 2001). Collaboration and exchange requires mutual trust. In the scope of sharing economy, actors need to understand: *"(1) states (conditions) of shareable assets in regard to capacity, presence and/or (idle time), capability; (2) previous experience in the sharing of same resource; (3) restrictions and compensation; (4) level of behavioral congruence of actors participating in the sharing; [and] (5) regulatory issues and dispute resolution"* (Baalsrud Hauge et al., 2019). Compared to physical markets, in a digital environment it is possible to set up transparent evaluation systems to address the quality and reliability of stakeholders (Schallmo et al., 2017). This means that labs can be contracted out to the network organization, as long as the necessary trust in the organization is present and it makes sense from an economic point of view (transaction cost).

Having identified the market conditions, a business model for digital labs is required that is tailored to the customers' and providers' demands, while fulfilling the trust in network organizations. Consequently, the first research question **(RQ1)** is: What are the success criteria for a sustainable business model of digital labs? This question refers to networked organizations and addresses the question of how an ecosystem for digital labs can successfully exist (Esposito et al., 2021). The second research question deals with the concrete business model of networked organizations. However, the offer for students should be of high quality and comprehensive. In addition, the lab should be operated in a way that guarantees access to the largest possible community. In adapting the business models of the leading providers of the sharing economy, a multi-sided platform would fit the concept. A multi-sided platform is an intermediary economic platform that brings together two or more different but interdependent customer groups; it is used, for example, by Airbnb (landlord and tenant), eBay (buyers and sellers), and Facebook (users, advertisers, and content developers). According to this concept, universities would offer various lab services, and students could meet their needs via appropriate platforms. This results in the second research question **(RQ2)**: What are the functional requirements of a multi-sided platform for digital labs? This paper focuses on answering these two research questions.

2.2 Research Methodology

As methodology the paper is following the design science research methodology (DSRM) in information systems of Peffers et al. (2007), consisting of six activities. Within the first activity, problem identification and motivation, the problem of underutilization of expensive labs and the potential of digitalization for shared labs for education purpose is addressed. The second activity, define the objectives for a solution, is to establish a sustainable business model that addresses the functional requirements for a multi-sided platform for digital labs. Third, design and development, is to create a multi-sided platform to reach sustainability for a digital lab sharing network. The fourth activity, demonstration, applies the business model as an artifact to a digital lab sharing case study that seeks to provide a marketplace for sharing digital lab resources between suppliers and buyers across institutional boundaries. Evaluation, as the fifth activity, uses a comparable industry example and surveys of industry and students to observe how user groups support the business model. Finally, the problem and its importance is discussed and communicated.

2.3 Literature Review

The criteria for sustainable business models and multi-sided platforms are described in this section, to address the design and development of the DSRM artifact. The literature review includes an analysis of the definition, framework, and taxonomy of business models. This is followed by an analysis of the core criteria of multi-sided platforms, which is intended to give an indication of the challenges faced to achieve the long-term goal of establishing a sustainable business model for shared lab environments. The literature review is based on Tranfield et al. (2003)'s three-step approach: (1) planning a review, (2) conducting a review, and (3) reporting and dissemination. First, the review is planned on the basis of RQ1 and RQ2. Second, the databases for the Journal of Business Models (JOBM) and the special issue Multi-Sided Platforms of The International Journal on Networked Business (vol. 29, no. 4 – Electronic Markets, 2019) have been analyzed. JOBM was chosen because of its focus on business models and the special issue because it addresses multi-sided platforms. Both journals are high-ranked international academic journals and include meta-reviews on the topics of interest. Data collection took place between December 2019 and February 2020. Altogether, 105 papers from the JOBM database and 10 papers from of the special issue of The International Journal on Networked Business were analyzed using title, keywords, and abstract. Of these papers, 34 were selected for detailed analysis. Five meta-reviews and one trend analysis are included in the literature review. The original works were published between 2013 and 2020. Third, reporting and dissemination are grouped into business model definition (BMD), business model framework (BMF), business model taxonomy (BMT), and multi-sided platforms.

2.3.1 Business Model Definition

The term business model was first used by Lang in 1947 and has been the subject of debate ever since (Lang, 1947). There is as yet no consensus regarding a definition. According to Cuc

(2020), the most relevant current authors (considering the number of publications and degree of influence) are Zott, Amit, and Chesbrough.

Regarding BMD, BMF, and BMT, the business model literature states the following:

- **BMD**: authors define business model differently due to a lack of consensus,
- **BMF**: a template for developing new or documenting existing business models and
- **BMT**: classify business models according to one or more characteristic criterion

Is a separate definition for digital lab business models needed? Would it increase sustainability? The necessity and relevance of BMD analysis is well reflected in the work of Jensen (2014). Initially, the concept was used to understand e-businesses (Timmers, 1998; B. W. Wirtz, 2010; Zott et al., 2011) and to facilitate the use of technology and innovation (H. Chesbrough, 2010; H. Chesbrough & Rosenbloom, 2002; Johnson et al., 2008). Market practice was ahead of academic research (Baden-Fuller & Haefliger, 2013; Casadesus-Masanell & Ricart, 2010), but business models still play an important role for various stakeholders in mobilizing resources in the entrepreneurial process (Jensen, 2014). Literally, doing "business" means carrying out activities or exchanging values, and a "model" is a representation of the reality with different levels of accuracy or detail. A business model is considered *"a highly complex entity that can only be represented through abstraction"* (Casadesus-Masanell & Ricart, 2010). Jensen (2014) developed a three-level vertical concept of BMD. Level 1 is just the abstract term "business model" for simple and practical use as a keyword with global and local meanings. For level 2, the author defines business models as *"a focal firm's core logic for creating, delivering and capturing value within a stakeholder network"* (Jensen, 2014). This provides a link between scientific and practical definitions with the domain, features, and structure. Level 3 is grounded on level 2, but the definition depends on the special research topic, with explicit focus on the domain (discourses/research gaps). For level 3, Jensen (2014) developed a horizontal view of understanding BMD: (1) the representational view, (2) the functionalist view, (3) the pragmatic view, and (4) the systemic view. Regarding the functionalist view, Jensen (2014) recommends that a BMF/patterns should be applied. Thus, the initial question of whether a BMD is necessary at all can be clarified. Based on Jensen's (2018) research, a separate BMD with a focus on digital labs as a research topic (level 3) and a BMF/pattern representing the functionalist view are required. Several authors combine the creation and capture of customer value within the BMD. Fielt (2014) specifies the creation of customer value on one hand and the way to capture customer value (for the creation of business/exchange value) on the other. According to Fielt (2014), the definition of business model is *"the value logic of an organization in terms of how it creates and captures customer value"*, focusing on the value logic of an organization. After reviewing the work of Amit and Zott (2001), Teece (2010), and Chesbrough (2010), Yrjölä (2014) agrees that a business model describes customers' and firms' value creation. Furthermore, it describes the selection and coordination of activities; a business model is a strategic instrument for innovation and differentiation (Yrjölä, 2014).

A common BMD and general understanding of business models does not exist. This paper treats digital labs as a special research topic, with an explicit focus on the domain; BMD is therefore defined in section 2.4.2. The next section takes up the recommendation of Jensen (2014) and considers the functionalist view of understanding BMD. To represent the functionalist view, there are BMFs that can be used as scaffolding and predefined BMTs. Questions arise as to how the different value propositions for buyers/students and lab suppliers can be highlighted and if these value propositions are related to the sustainability business model. First, the BMFs are examined in detail to determine how business models can be mapped and value propositions identified. Subsequently, which existing BMTs can be used and which functions should be adapted to create a sustainable business model for digital labs is discussed.

2.3.2 Business Model Frameworks

The term BMF, which is used differently in the literature, relates to what business models consist of compared to the BMD (Fielt, 2014). According to Osterwalder et al. (2010), a BMF consists of building blocks; according to Wirtz et al. (2016), it consists of components; according to Morris et al. (2005), it consists of questions; and according to Chesbrough and Rosenbloom (2002), it consists of functions. What they all have in common is that they attempt to describe business models in more detail using these elements. A BMF not only defines the elements but also represents the relationship/hierarchal structure between the elements. According to Fielt (2014), five BMFs are most commonly used. 1) The Business Model Canvas (BMC) by Osterwalder et al. (2010) is the best known and most widely used BMF (Fielt, 2014; Lund & Nielsen, 2014; Sorri et al., 2019). It is designed to describe, visualize, evaluate, and modify business models. BMC consists of nine elements, where the value proposition connects the supply side with the customers (Osterwalder et al., 2010). 2) Weill and Vitale (2001) developed the e-business model schematics BMF. Using the elements of Timmers (1998), the roles and relationships, major flows of product, information, money, and revenues of the business model are illustrated (Fielt, 2014). 3) Chesbrough and Rosenbloom (2002) created the so-called technology-market mediation model, using value proposition, market segment, value chain, cost structure and profit potential, value network, and competitive strategy as BMF elements. 4) The entrepreneur's business model of Morris et al. (2005) is iterative using an increasingly specific three-level approach. The foundation level is defining basic components, the proprietary level is creating unique combinations, and the rules level is establishing guiding principles (Morris et al., 2005). In each of the three BMF levels, six factors are covered that are related to the offering, market factors, internal capability factors, competitive strategy factors, economic factors and growth/exit factors (Morris et al., 2005). 5) The four-box business model of Johnson et al. (2008) refers to the customer value proposition, the profit formula, key resources, and key processes. All BMFs use the business model dimensions that cover the core questions about creating and capturing customer value in terms of who, what, why, and how (Fielt, 2014). The BMFs differ but have a very similar and comparable basis. Various authors have dealt with more detailed comparisons of BMFs. An overview can be found in Di Tullio (2018); however, she does not rate the different BMFs. All BMFs have certain advantages and disadvantages.

The authors of this article decided to use Osterwalder's (2010) BMC, the most widely used in science and economics. This model is also recommended by the German Ministry for the Founders of New Business. However, the disadvantages of the model mentioned in the literature should be considered. Lund and Nielsen (2014) analyzed the advantages and disadvantages of the BMC. They used the BMF to discuss the "Hows" and "Whys" of a company's activities and choices. In this way, the strengths, weaknesses, and potential of a business model become apparent. First, the BMC has limitations in terms of the static nature of the BMF, which inhibit innovation (Lund & Nielsen, 2014). Second, the BMF reaches its limits in representing the value proposition of all stakeholder when many different companies and individuals form a network in a new business model (Lund & Nielsen, 2014). To address the first disadvantage, an iteration of the model is required that could be addressed by business model innovation (BMI). BMI is described as a technology, process, product, and organizational innovation (H. Chesbrough, 2010), which is linked with sustainability by Cuc (2020). Zott and Amit (2010) describe BMI as the process of adding novelties, linking activities, and changing one or more elements of the business model. Thus, it describes the ongoing process that is required to ensure that a business model remains sustainable. Different variations of BMI can be found in the literature (Gassmann et al., 2014; B. Wirtz & Daiser, 2017). Cuc and Miina (2018) added the strategic perspective of classifying the life cycle phases of a business model to the concept of BMI. Accordingly, a business model develops over several phases with different degrees of innovation. In each phase, a strategic direction is required, such as competitive advantage, improvement or renewal of the business model through innovation, improvement of competitiveness, and an increase in business performance (Julio E. Cuc & Miina, 2018). In the development phase of a business model, the strategic direction and thus the innovation is determined, but in order to achieve long-term sustainability BMI should be taken into account. BMI can be seen as an important tool to continuously monitor whether the value proposition (Jensen, 2014; Yrjölä, 2014) is being fulfilled by customers and suppliers. The second disadvantage can be addressed by the Platform Canvas (Sorri et al., 2019). It is a guide to support the BMC and particularly addresses the platform ecosystem, the participants, and the promotion of innovation. The Platform Canvas (Sorri et al., 2019) uses eight key characteristics of platforms, which are (order does not reflect the popularity): (1) value: value creation potential of the platform, (2) monetizing: capturing the value, (3) producers: side one of the platform, (4) users: side two of the platform, (5) filtering: efficient value exchange to increase matching, (6) governance: control, rules, access control, and trust, (7) resilience: adaptive to change (modular, plug-n-play), and (8) network effect (crucial characteristic): the ability to scale with minimal investment.

For the purpose of the digital lab, the BMC was chosen because it offers the advantages of user friendliness, practical relevance, visualization of content, and is also comparable to other BMFs (Fielt, 2014; Lund & Nielsen, 2014; Lüttgens & Diener, 2017; Petri, 2014). However, in order to take into account the disadvantages of the BMC (Lund & Nielsen, 2014) and the platform-specific characteristics, the Platform Canvas (Sorri et al., 2019) must also be applied. In addition, the BMI concept of enriching sustainability can help to continuously adapt the value proposition. Now that a BMF has been selected, whether there are already comparable platform solutions on which we can build can be determined. Is it possible to use similar proven examples (BMT, see section 2.3.3), such as the prominent market examples mentioned in section 2.1? Or is it necessary to develop it ourselves? The concept of BMTs is addressed in the following section.

2.3.3 Business Model Taxonomies

In the literature, there are several approaches for clustering BMTs. Instead of the term taxonomies, analogies, patterns, or classifications are often used in the literature. The basic concept of taxonomy goes back to Plato and Aristotle and relates to evaluating similarities and differences. A BMT is a classification of objects into groups or classes based on their business model similarity (Lambert, 2015). These similarities are interpreted differently by different people, as the analysis shows. Early business model classifications, such as that by Applegate (2000), used simple identification categories, such as distributor model, portal model, producer model, or infrastructure provider model. Others are based on criteria such as customer profile, market configuration factors (Tapscott et al., 2000; Timmers, 1998), transaction factors, or marketing strategy (Weill & Vitale, 2001). Special digital BMTs are based on business models for the internet/web (Afuah & Tucci, 2001; Rappa, 2019; Timmers, 1998) or atomic e-business models (Weill & Vitale, 2001) . More recent BMTs are the 19 analogies by Johnson (2010), the 55 patterns by Gassmann et al. (2014), and the five BMTs of Osterwalder et al. (2010).

As an innovation business model for digital labs is to be established, with high quality, comprehensive offers, and availability to the largest possible community, many models mentioned above can be excluded. Lund and Nielsen (2018) clustered business models that are capable of unlocking exponentially increasing returns to scale. Learning from this characteristic could help to enable a sustainable lab ecosystem, achieve sustainability, and gain access to a community that enhances the contents. The attributes of scalability described by Lund and Nielsen (2018) are that a business model is flexible and the business potential should not be limited by physical or tangible assets, which can also be achieved by digital labs. Nine BMTs are captured as platform concepts that address the demand of labs' suppliers and students, including multi-sided platforms. Compared to multi-sided platforms, however, they do not get to the heart of the matter. The approach of Adaptive (H. W. Chesbrough, 2006), is to establish an ecosystem that is based on its own technology landscape . It should be applied to the digital labs, but the technology-driven approach is not at the core of the matter. The concept of a collaboration platform (Timmers, 1998) refers to providing a platform with a toolkit and an information environment for cooperation between companies. While promising, the BMT does not address platforms with different user groups, as we would have with digital labs. The facilitation of transactions based on the brokerage taxonomy (Johnson, 2010) is a task but does not correspond to the core business of the marketplace. The multi-sided platform for digital labs reduces, transaction costs, is tailored to the demands of customers and providers, responds to their independent value propositions, lives through the community, promotes high quality, and is considered a market-disruptive model within the sharing economy. In addition, in the digital economy, multi-sided platforms are a strong BMT due to their adaptability, ability to deal with complexity, rapid scale-up due to the network effect and value capture (Abdelkafi et al., 2019). In order to learn from the model properties, specifics and limitations of the business model are elaborated in the following section to show the functionalist view of multi-sided platforms for digital labs.

2.3.4 Multi-Sided Platforms

Apple, Airbnb, eBay, Uber and Google are successful examples of organizations that have managed to establish an ecosystem using a multi-sided platform. Several definitions of a multi-sided platform can be found in the literature (Chakravarty et al., 2014; Gawer & Cusumano, 2014; McIntyre & Srinivasan, 2017). The definition of Osterwalder (2010) is commonly used:

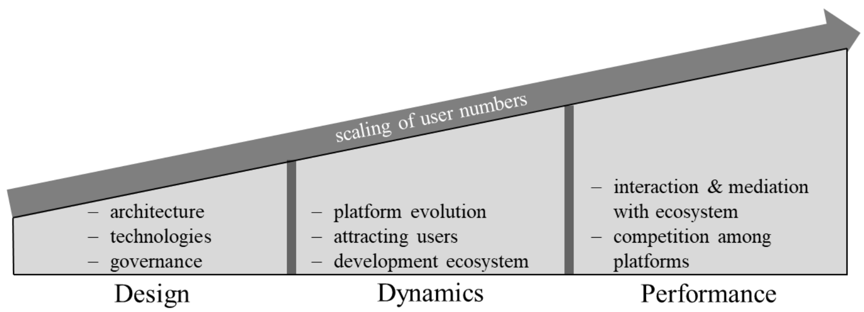
> *"Multi-sided platforms bring together two or more distinct but interdependent groups of customers. Such platforms are of value to one group of customers only if the other groups of customers are also present. The platform creates value by facilitating interactions between the different groups. A multi-sided platform grows in value to the extent that it attracts more users, a phenomenon known as the network effect."*

In short, the core elements are hubs or intermediaries for the exchange of values between interested parties and suppliers from two or more markets (Zhao et al., 2019). In the case of a digital lab network, the interested party comprises, for example, students (collectively called the buyer) and the suppliers are universities (or providers, collectively called the supplier); both sides can be expanded to include other stakeholders. The peer-to-peer marketplace is the actual platform on which joint exchange and coordination service take place. The marketplace aims to bring together the supplier of a given resource with the party (two or more) interested in using that resource; this is known as matching (European Commission, 2013). The main difference is that the marketplace does not acquire ownership, of the traded resource and therefore does not influence the way it is presented or the price. The conditions for sharing are therefore directly controlled by the supplier and the buyer. The digital lab supplier must therefore keep their offers and prices attractive in order to attract and keep the buyer. Commercial marketplaces all host a platform or online marketplace through which matching takes place; it can be demand-driven, supply-driven, or a combination of both (European Commission, 2013). More users increase the value of the marketplace, the so-called network effect (Abdelkafi et al., 2019). Eisenmann (2006) distinguishes between two types of network effects, same-side (or direct) effects and cross-side (or indirect) effects, where the value of the marketplace is measured based on the number of same-side or cross-side participants. The cross-side network effect is measured between the lab supplier and the buyer side.

If the marketplace has no influence on the offers, how can it generate revenue? The marketplace can use two forms of income (Behrendt et al., 2019), transaction-based commissions and non-transaction-based or transaction-independent commissions (Eisenmann et al., 2006). Transaction-based commission is based on the successful matching of supplier and buyer; a service fee is charged on the matched price/fees. The non-transaction-based commission is not related to the matching; income is generated by the sale of advertising space, membership fees, subscription options, or registration fees for using the marketplace. Both commissions are subject to risks; in the case of the transaction-based commission, the added value of the marketplace can be questioned for each transaction. The non-transaction-based commission can be an initial obstacle and may have a frightening effect. The marketplace owner should find a commission system, taking into account the impact on growth and willingness to pay. In most cases, the networks have a subsidy and a money side (or charge side). If the marketplace can reach enough users on the subsidy side, the users on the money side will pay to reach them (Eisenmann et al., 2006).

According to Henseling et al. (2018), the challenges of a multi-sided platform are: (1) strengthening user trust, (2) further development of marketplace offerings, and (3) acquisition of new user groups. Loss of trust in the network organization would result in the collapse of the network effect. If a digital lab is booked but not available in the expected condition, the buyer has no benefit at all. However, if the buyer of the lab does not handle the situation carefully, the suppliers stay away. How trust can be strengthened is the greatest challenge of the sharing economy and has been discussed by many authors from different disciplines (Baalsrud Hauge et al., 2019; Behrendt et al., 2019; Goudin, 2016; Heikkilä et al., 2014). The challenges are also described in Abdelkafi et al. (2019), as shown in 0, whereby they are grouped according to the marketplace life cycle phases. A marketplace life cycle consists of three phases (Abdelkafi et al., 2019; Otto & Jarke, 2019): (1) design: technological architecture and innovation of the platform (software and hardware), (2) dynamics: evolution of the platform and ecosystem by attracting users and adding new functionalities, and (3) performance: scaling, growing, and succeeding in competition. This approach is somewhat similar to BMI, where the business model and tasks are adapted to the current phases and associated challenges.

Figure 2: Challenges of Multi-Sided Platforms Within the Life Cycle Phases, based on Otto and Jarke (2019) and Abdelkafi et al. (2019)



In summary, multi-sided platforms have some specific features that should be considered as a business model. First, the two parties (buyer and supplier) must be addressed individually. Second, the type of commission to be applied has to be worked out, which is directly related to the network effect by reaching as many cross-side participants as possible. This is also where the core challenge begins; the marketplace must create trust among the parties in the network organization, and the marketplace offering should be further expanded.

2.3.5 Findings of the Literature Review

The literature review based on JOBM and the special issue could provide comprehensive insights into the current research on business models and are critical to the design and development of the DSRM artifact. The sources have proven to be valuable due to their consistency and thoroughness. Before the theoretical construct is applied to digital labs, it is summarized below in light of the research questions.

Modern definitions of sustainability refer to ecological, economic and social aspects (Ahrend, 2016; Sihn-Weber & Fischler, 2020). With regard to digital labs, it is essential to note that economic innovations should be integrated into the business model and that these must also increasingly fulfil ecological and social goals. The intention is that through the right choice and application of business model, sustainability can be achieved. Three elements are necessary to successfully implement a business model: (1) a BMD, (2) the use of a BMF, and (3) the application of a BMT. (1) A BMD helps to mobilize resources in the entrepreneurial process. The BMD must not only show the value proposition for the organization but also for its customer groups. (2) The application of a BMF shows the functionalist view, the advantages and disadvantages, and the correlations and dependencies of a business model in discussions with stakeholders. Various models exist, and the BMC of Osterwalder et al. (2010) has been chosen as a useful one for the digital lab case. However, the BMC also has pitfalls, which should be specifically addressed, for example, with the help of the Platform Canvas (Sorri et al., 2019) and BMI. The Platform Canvas can be used as a supplement in the successful implementation of platform-related business models, and BMI can be used to achieve economic sustainability within the life cycle phases. (3) By applying a BMT, special characteristics of a business model can be classified. In our case, the scalability of the business model can be achieved by the new distribution channels, liberation from traditional capacity constraints, the outsourcing of investments, the use of partners who work for free, and the implementation of platform models (Lund & Nielsen, 2018).

The multi-sided platform is convincing due to the approach of the two shared user groups, whereby the marketplace itself offers added value by facilitating interactions between the different groups. In addition, the multi-sided platform lowers transaction costs, is tailored to the demands of the buyer and the supplier, responds to their independent value propositions, lives through the community, promotes high quality, and is considered a market- disruptive model within the sharing economy. In order for the marketplace provider to be successful, the highest possible cross-side network effect must be created. This can be achieved by an attractive commission system, trust within the network organization and a service framework for the supplier and the buyer. Trust in the network organization is of utmost importance. Marketplace providers, the lab supplier, and the buyer should have a strong trust relationship because they need to rely on each other. A lack of trust can have both organizational and social consequences for the individual and the group. Furthermore, a continuous iteration process maintains the attractiveness of the platform. Similar to the BMI principle, the development of the marketplace must be reinvented, and the actual way in which value is created and captured has to be transformed in the three life cycle phases of the multi-sided platform. The main challenges here are the strengthening of user trust, the development of offerings, and the acquisition of new user groups to scale the user numbers.

The demonstration of the theoretical construct is divided into two steps. First, the general feasibility of a multi-sided platform for digital labs is demonstrated using the Open Digital Lab for You (DigiLab4U) research project as a case study. This allows on the one hand to assess the general feasibility and on the other hand to make the value dimension of the actors more tangible. The results of the case study and the literature review will be used to outline a concept for the multi-sided platform. In a second step, the functional perspective of the business model for digital labs is developed by applying the BMC and further working out the characteristics using the Platform Canvas. The BMC separately represents the two value dimensions of the supplier side and the buyer side. Afterwards, the business model is evaluated based on the two actors. For this, the business model transformation of the supplier side is evaluated and the intention of the buyer side to use labs on the basis of industrial customers and students is surveyed.

2.4 Multi-Sided Platform for Digital Labs

In this section, as the fourth DSRM activity demonstrates the artifact, a business model for a multi-sided platform for digital labs is developed. The feasibility of the theoretical concept is therefore tested in the context of a case study for digital labs in a shared environment. Next, the business model for digital labs artifact is defined and the concept outlined. As an artifact for problem solving, the BMC is developed for elaborating the functional perspectives and Platform Canvas is applied for ensuring the sustainability of the platform ecosystem.

2.4.1 Feasibility Check Using DigiLab4U Case Study

With the help of the research project DigiLab4U, it will be demonstrated that the multi-sided platform is suitable as a BMT and can support the sustainability of the network. DigiLab4U connects organizations teaching and researching in the STEM area. The common basis of the project members, four German academic institutions and one Italian one, consists of practical education, training, and research in physical labs. The project intends to offer a digital lab environment that enables the networking of real and virtual lab facilities across locations within the network organization. The networking of the labs is intended to save human and financial resources and to increase the number of users previously restricted to their own institution. For example, students in Stuttgart should be able to access labs in Bremen or Parma and vice versa. Furthermore, the digital labs are to be integrated into digital teaching content via a platform and supplemented with the latest educational methods in engineering related to education 4.0. In order to reach a larger number of labs and students in the network, eight additional external labs will be directly supported by a financial incentive for the mobilized in the hope that more labs will subsequently join the network indirectly.

Moving DigiLab4U Towards a Multi-Sided Platform

There are several steps to be considered when moving the DigiLab4U research project towards a multi-sided platform. The closed circle of the network organization must be opened for further suppliers and buyers of digital lab offerings to support the cross-side network effect. The marketplace would consist of the digital labs on one side and the buyers accessing the labs on the other side, linked by the marketplace for the purpose of matching. The differentiation of the stakeholders by (lab) supplier and buyer side is shown in Table 1.

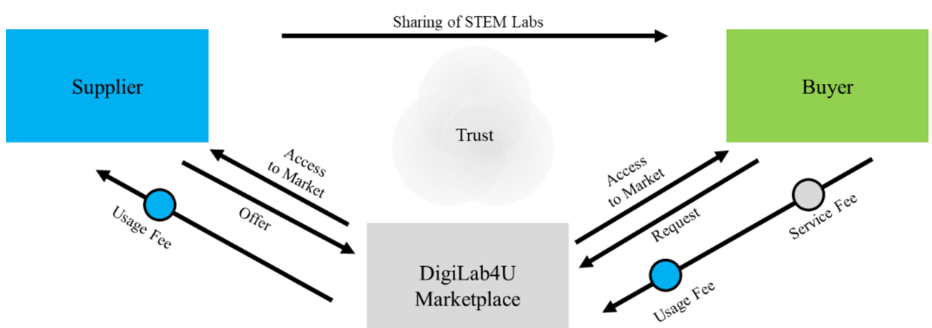
Table 1: DigiLab4U Stakeholders in the Multi-Sided Platform Business Model

Stakeholder	Supplier Side	Marketplace	Buyer Side
DigiLab4U		X	
Universities	X		X
Research institutions	X		X
Industry	X		X
Students			X
Professors/lecturers	X		X
Researchers			X

The supplier side could consist of various labs of universities, research institutions, industry, and professors/lecturers. The added values of the supplier side are an additional source of income and access to the professional community (Goudin, 2016). There are several examples of digital labs that could be potential suppliers in the marketplace, such as TU Dortmund University (running material characterization tests remotely with a robot arm), TU Braunschweig (operating a teaching and learning factory for Energy and Resource Efficiency, Digitalization and Urban Factories), or the Digital Capability Center Aachen (learning factory for the I4.0 value chain) (Haertel et al., 2019). There would be a growth opportunity for the network effect, as almost every physical lab could be retrofitted with digitalization technologies. The buyer side would consist of students (bachelor to doctorate levels), researchers, professors/lecturers, universities, industrial companies, and research institutions. Benefits for buyers by using the marketplace would be access to unique labs independent of time and place and access to more digital education content. The current market segmentation into STEM areas and buyer groups (bachelor to doctorate levels) restricts the network and requires different lab characteristics and education levels, but the restriction also has advantages for forming the network community. Furthermore, the added value of the marketplace must be visible for both sides. The basis for this could be a service framework for the technical, didactic, and organizational landscape forming an ecosystem around the marketplace. Next, the commission system is a fundamental choice, and both transaction-based and non-transaction-based commissions have advantages and disadvantages. However, the buyers accessing the labs will be the paying/buying network side, unless the revenue is generated externally, for example, through advertising, which is not initially assumed.

Figure 3 illustrates the DigiLab4U concept for multi-sided platforms. The supplier (blue) is sharing STEM labs with the buyers (green) via the DigiLab4U marketplace (grey), taking into account the service framework. A fee-based commission system is used for the purpose of explaining the concept.

Figure 3: DigiLab4U Concept of Multi-Side Platform Business Model, based on Singh and Singh (2017)



The feasibility of using the multi-sided platform as a business model for digital labs could be proven in general by the DigiLab4U case study. The sustainability of the network is supported by the BMT, as the supplier side is interested in placing an attractive offer to attract many customers, and the service framework of the marketplace can support this. Open questions remain, namely, which relationship/hierarchical structure exists between the business model elements, which value dimension (like service framework) the marketplace offers, and how the commission system is structured. Because the general feasibility has been proven, the business model for digital labs can now be created on the basis of the theoretical construct.

2.4.2 Multi-Sided Platform for a Digital Lab Marketplace

This section aims to establish a multi-sided platform business model for digital labs by defining the model, elaborating the characteristics using Platform Canvas, and creating the functional perspective using the BMC.

Business Model Definition

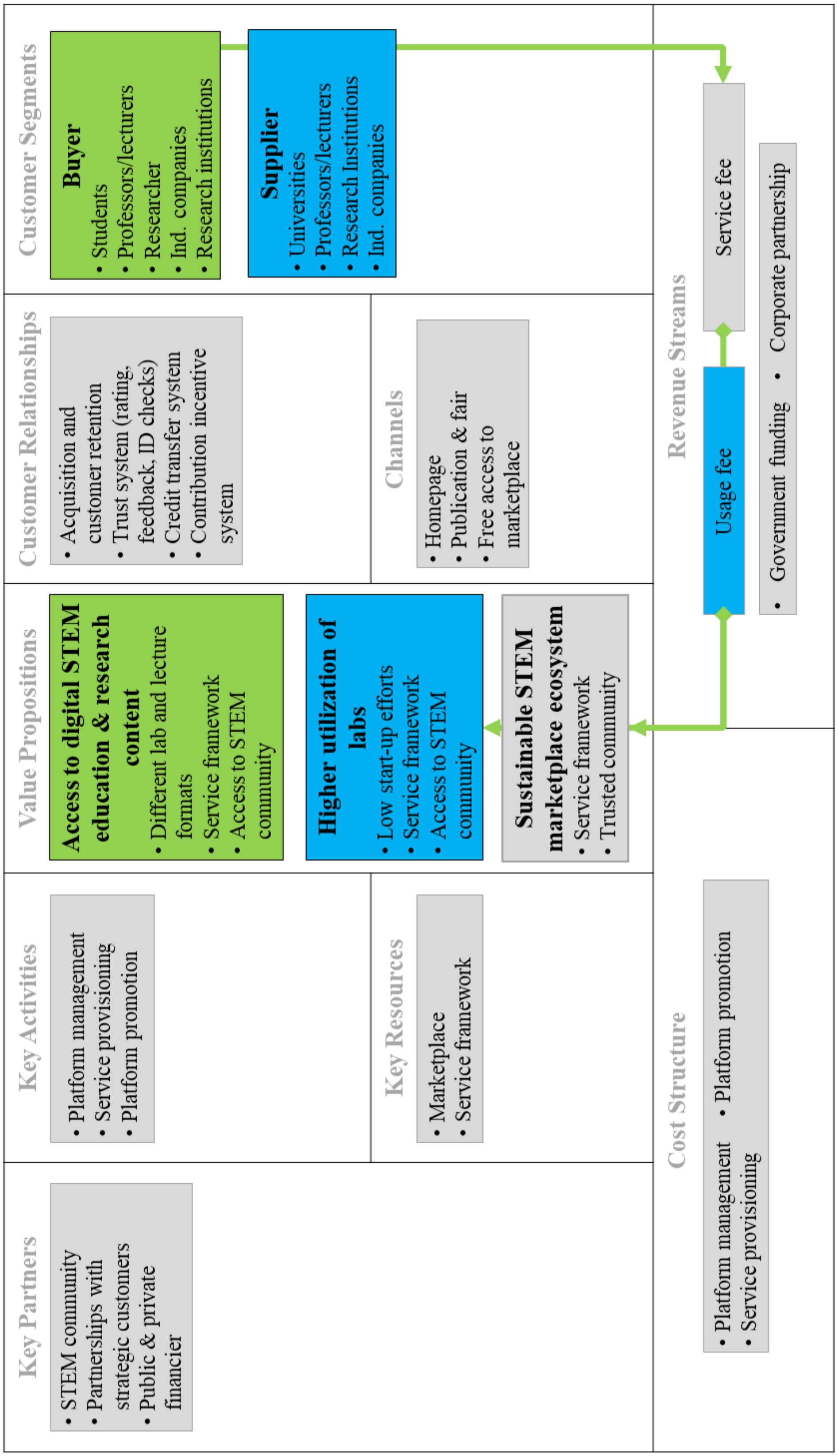
Multi-sided platform for a digital lab marketplace is defined as a sustainable digital lab ecosystem that provides a marketplace for digital STEM education and research. The marketplace facilitates the lab supplier to achieve additional revenue and the lab buyer to maximize the education and research process.

The BMD is specific for the digital lab research topic (Fielt, 2014; Jensen, 2014; Yrjölä, 2014) and describes how the digital lab business model creates, delivers, and captures the value logic. It consists of several elements: (1) Sustainable digital lab ecosystem: this distinguishes the marketplace from a purely profit-oriented model and concerns sustainability in the sense of network organization. (2) Marketplace for digital STEM education and research: this element addresses the mission of the business model. The model should act as a platform in the specified customer segment, STEM education and research. (3) Marketplace facilitates the lab supplier and the buyer: this describes the value proposition of the marketplace. The marketplace facilitates matching for the lab supplier and the buyer. (4) Lab supplier to achieve additional revenue: the first stakeholder group comprises the lab suppliers, who have a higher utilization and thus a further source of revenue by sharing the labs. (5) Lab buyers to maximize the education and research process: the value for the second stakeholder group is the education and research content based on the digital labs. By bringing together the marketplace, the lab supplier, and the buyer, the network is expected to grow. Next, the technical construct of the business model is created by extending the BMC with the Platform Canvas.

Business Model Canvas

The BMC with the nine elements is shown in Figure 4. The customer segment buyer with the value proposition and money flow is highlighted in green, the customer segment lab supplier with the value proposition and revenue stream is highlighted in blue, and the marketplace elements are highlighted in grey. The individual elements and their interactions are explained below.

Figure 4: Multi-Sided Platform as Business Model for Digital Labs, using the BMC of Osterwalder et al. (2010)



Value Proposition: The value proposition is prepared with the BMC especially for buyers (green), suppliers (blue) and the marketplace (grey). There is a financial benefit for buyers in gaining access to lab facilities and learning content at a lower price than if they set up the same service on their own premises, including the cost of hardware, software and labor. They also get flexible access to STEM digital education and research content provided by suppliers and marketplaces. Different lab and lecture formats can be utilized without the need to build up their own extensive knowledge in areas of education 4.0. The service framework supports the transactions and makes them as easy as possible for the customer. The STEM community also provides access to peers for research or education. The main motivation of the supplier to develop a revenue stream through the lab is indicated by the green arrow. The value proposition for the supplier includes the unneeded customer acquisition cost, co-financing of existing lab infrastructures, assisting in the remote accessibility of lab equipment for their own students, access to community and enhancing their reputation in research and education. In addition, access to the STEM community is highly valued, especially for companies and public institutions, in order to establish new contacts. The marketplace brings the two customer segments together through the sustainable STEM marketplace ecosystem, which is maintained by a service framework and a trusted community and increases the goal of an overarching network effect.

Customer Segments: Besides the buyer and supplier segmentation, STEM is addressed as a special community. Buyers can be institutional (universities, companies, research institutes) or individual (students, professors/lecturers, researchers) and may require different agreements/contracts. The green arrow indicates that the money flow is coming from buyers. Because suppliers, such as universities or companies, can also become buyers, a compensation scheme is conceivable. In return, a supplier of one lab can use another lab.

Revenue Streams: The main source of revenue will come from the buyers, who will pay a usage fee for the use of the labs. As the green arrow shows, the usage fee goes to the supplier of the used labs and the service fee goes to the marketplace as service fee. Other sources of income for the marketplace could be government funding or corporate partnerships, as digitalization in research and teaching is a funding issue.

Customer Relationship: Acquisition and customer retention is the primary task and is supported by the trust system. A trustworthy marketplace is the key to success—for the supplier in that sensitive labs are used correctly and for the buyer who uses the lab in the expected way. A transaction rating, a possibility of feedback and an ID check should support this. A credit transfer system and a contribution incentive system could also increase the activity of the community.

Channels: Access to the marketplace is provided free of charge, which activates customers and has a positive effect on the network effect. This is supported by different channels for addressing customers. Individuals are addressed through the homepage, trade fairs and scientific publications; for institutions, personal contact may also be required.

Key Partners: Strategic partnerships with professors/lectures, researchers, industrial companies, universities and research institutions can help to win new customers, expand educational content and extend and improve the service framework. Lab availability is a key quality criterion for online labs; therefore, strategic long-term partnerships are preferred. However, professors/lecturers can leave a university or change their job. Therefore, a contract should support a structured handover procedure for internal or external alternative supporters. Thus, the partnerships can also influence the sustainability of the platform. The financiers provide public and private funding and donation programs.

Key Activities: Platform management, service delivery and platform promotion are the key activities that should be performed by the marketplace. The further development and operation of the platform expands the standardized service framework and enables quick and easy access for supplier labs and buyers.

Key Resources: The resources are the marketplace and the service framework. The community, user and research data and the trust system could also be key resources, but as they are not physical assets this is not directly mentioned.

Cost Structure: The costs of the marketplace are determined by the operation of the infrastructure, the development of the marketplace, the acquisition of the community, the promotion of the marketplace and the services offered. Some of the costs can be directly allocated to the transaction, which creates transparency about the cost drivers.

Platform Canvas

The Platform Canvas supplements the BMC by addressing key characteristics of the digital lab platform ecosystem.

Value: A sustainable STEM platform ecosystem describes the added value of the marketplace, which consists of three components–STEM as a delimited market segment, an ecosystem as service framework surrounding the marketplace and a sustainable marketplace consisting of two participants supported by a trust system.

Monetizing / Value capture: The main revenue stream relies on transaction-based commissions (Behrendt et al., 2019). A transaction fee for matching a supplier and a buyer (money side) is charged. The lab supplier offers a self-determined price for a buyer to use the lab, and the marketplace charges a service fee on the transaction. The market balance promotes sustainability and high-quality offers. The service fee should be adapted to the diversity of the service framework (continuous development process or BMI) and can be adjusted for strategic partners.

Value Producers: The producers of value are the lab suppliers, such as universities, research institutions and industrial companies, who are seeking more intensive use and thus additional income for the labs (Eikaas et al., 2003). For the lab suppliers, the value proposition consists of offering their lab services to an existing user base and handling the transaction via the marketplace. Suppliers are motivated to participate in the market because of lower customer acquisition costs, participation in new markets, lower costs for advertising and brand awareness, the service framework, mutual trust, and direct access to the community. In this way, the marketplace reduces the frictional losses in order processing through billing and booking systems; the effort put into didactic–technical preparation of the contents enables tailor-made offers and creates trust among the market participants. As a result, the effort for the lab suppliers is low due to the standardization of the marketplace, while the learning success for the buyers is high. In line with the transaction costs, it can be assumed that suppliers prefer integration into an existing marketplace ecosystem rather than creating their own solution (Tapscott et al., 2000).

Value Users: Buyers get flexible access to digital STEM labs and learning content regardless of time and place. The buyers are categorized into three different groups for teaching, training, or research. Professors and lecturers use the marketplace for teaching purposes. A modular teaching offering with practical labs addresses their educational needs. Bachelor's or Master's students, private individuals, or industrial companies can use the marketplace for learning purposes. Advantages for these users are validated, and practical learning contents, structured education paths, innovative teaching methods according to education 4.0, certifications (e.g. badges), and the digitalized remote and therefore flexible access to educational content are provided by the marketplace. Use of the marketplace may be based on intrinsic or extrinsic motivation; for example, students are often obliged to follow the technical conditions of a lecture in a curriculum. Besides supporting learning and teaching purposes, the labs can also be used for research purposes. Researchers, companies, and research institutions use the labs to pursue technical STEM topics and gain access to research data; this group stimulates the sustainability and innovation of the labs and the marketplace.

Filters: Market segmentation is considered the key to success in competitive markets. A possible segmentation towards a lab community domain can address current educational and research topics such as STEM or IoT/I4.0 educational programs. It addresses different groups (suppliers/buyers) with the same needs and wants. Therefore, forming a community is easier than in a non-segmented market. A customer-specific search, filter and matching function makes the marketplace accessible through a) customer data such as language, degree, course of studies, semester, university, recommendations, learning paths based on badges, certifications, and mentor/mentee promotion and b) lab data such as lab subject domain, type, language, or education level.

Governance: The marketplace provides a service framework and a trust model for lowering the barriers to entering the marketplace. The service framework consists of technical, didactic, and organizational components that form an ecosystem around the marketplace, for example, standardized architecture, interfaces to third-party systems such as learning management systems, security and safety mechanisms, data protection and privacy, backup systems, data management, booking and accounting tools, order processing, trust systems, virtualization systems such as virtual and augmented reality (VR/AR), learning analytics, and serious gaming. The components are to be understood as an initial collection of ideas and should be adapted to the current needs of the customer as a continuous development process according to BMI. Current trust mechanisms of digital platforms use the 1–5-star rating system. The authors research a much more precise trust model that visualizes the current trust behavior in a shared environment (Baalsrud Hauge et al., 2019). Because the current relationship is dynamic due to the impact of external events, a transaction-based operationalization is pursued. The model should reflect: *"(1) states (conditions) of shareable assets in regard to capacity, presence and/or (idle time), capability; (2) previous experience in the sharing of same resource; (3) restrictions and compensation; (4) level of behavioral congruence of actors participating in the sharing; (5) regulatory issues and dispute resolution" (Baalsrud Hauge et al., 2019).* The transparent system can be operationalized over time and enriched with additional components.

Resilience: A technical, organizational and financial distinction for resilience is made. The use of a standardized platform architecture and standardized interfaces increases the technical resilience. From an organizational point of view, there could be changes of lab personnel; however, an overall agreement with the organizations can prevent this. Financial resilience must be achieved through a sustainable business model, which cannot be achieved with temporary resources alone.

Network effects: The network is stimulated by subsidies and a money side effect. A registration option that is free of charge for both sides allows scaling with minimal investment. The subsidy side is represented by the lab supplier, who get access to the service frameworks and thus creates the highest quality lecture and lab content. The money side is represented by the buyer, who pay for access to lecture and lab content. Strategic partnerships –for example, with universities that offer labs, students, and marketplace content—lower the access barriers to the platform for members of these partner universities. It is important to quickly reach a critical mass of suppliers and buyers, which could be achieved by first-mover rewards. Temporary promotions or test access could increase the effect in the short term.

2.5 Evaluation

In this chapter, three user group evaluations are used to assess how effective the artifact is based on the sustainability and functionality requirements of the developed business model. First, the experience from the serious game industry, which has undergone a comparable transformation of products to service-oriented products, was compared with that of the lab supplier side. Second, industry companies were interviewed in semi-structured survey about their intentions to use a platform to access digital labs. Finally, the intentions of students to use online labs were also collected using a semi-structured survey.

Experiences from the serious game industry should help to better understand the challenges of the supplier side. The serious game industry faces similar challenges, according to a report by the Game and Learning Alliance (GALA) which we saw at labs for education (Baalsrud Hauge et al., 2014). Serious game business models and strategies are often characterized by a niche strategy, are highly individualized, are cost-intensive, are subject to low reusability, and the funding scheme shows a high level of involvement from government or non-profit organizations (Baalsrud Hauge et al., 2014). Similar to digital labs, market expansion can be achieved either by increasing the number of potential customers or by finding radical approaches to reduce costs and generate new revenues, otherwise they will remain in quality niche markets. A transition to a service-oriented business model, shows on the basis of two examples how thereby new markets are entered (Baalsrud Hauge et al., 2014). Here, the tangible product is not the unique selling point, but a range of (customizable) services. The end user gains access to the product via the Internet as a sales channel as part of a service provided by experts. The providers thus achieve that the business model used is dynamic, responsive and adaptable to new trends. For sharing digital labs towards a service-oriented business model, the reduced product orientation means that generic labs should be adapted to the individual needs of customers. Here, a key to success lies in the early discovery of market changes such as STEM or IoT/I4.0 educational programs, the focus on reusability and interoperability of teaching and learning content, and responding to customer needs in terms of service design (value proposition) such as with a service framework.

To understand the industry side of the multi-sided platform, a semi-structured online survey (because of Covid-19 pandemic) was conducted with qualitative and quantitative questions. The first section of the survey collected data regarding the respondents' affiliation, which was collected exclusively for quantitative analysis. The second section asked whether or not respondents had ever used digital labs. Based on their responses, two patterns were defined, section 3 with questions for respondents who have already used digital labs and section 4 with questions for inexperienced users. In both sections, the questions relate to (1) the type of lab used or likely to be used, (2) the quality of the service offered or expected, (3) benefits and knowledge acquired or expected, (4) whether there was a platform managing access to content or whether it was intended to improve the quality of the service, finally (5) how much it cost to use the lab and related services (and relative perceptions in spending), or whether the cost was intended to be reasonable. Twenty-one entrepreneurs and practitioners (18 managers or chief officers of technical divisions) from the northern Italian area participated in the survey, 16 of whom work in the manufacturing sector and 5 in the tertiary services sector. The results show that of the participants, no one has used a digital lab yet. However, 67% say they view digital labs as useful for continuously improving business practices or the portfolio of offerings to customers. 57 percent of respondents expect digital labs to allow them to conduct tests on material they would not otherwise have access to. 57% of respondents cannot assess what added value a marketplace can bring to the player. However, 48% do not reject the possibility of a third-party provider managing the service framework, and the main reason is the trustworthiness of the system (48%). Finally, regarding the financial sustainability of digital labs and marketplaces, 67% of respondents believe that they can be considered as service offerings for customers to pay for. Pay-per-use is the preferred payment typology (67 %), while 19 % of respondents link the payment typology to the service provided. Further results emerged from the quantitative perspective. The industrial customers repeatedly made reference to various cloud software offerings which, in their view, are comparable solutions and could therefore be easily integrated into everyday business. Of interest here are simulation software or special technology such as AR systems, digital twins or artificial intelligence, which represent a greater challenge for small and medium-sized companies, for example. In general, there is no question about the benefits, as there are high hopes for digital labs (easy access to resources and experiments, knowledge and experience, easy to use, limiting the company's investments in specific simulation tools, save time and possibly money). Concerns about their use have repeatedly been data security and the outflow of core knowledge from the company. They expect a marketplace provider to make the lab easy to use, to offer support, to speed up processes and to make labs findable as services (*"market service should focus on effectiveness more than efficiency"*).

Finally, students' intentions to use digital labs were surveyed. A semi-structured online survey with qualitative and quantitative questions was conducted in February through April 2021. Respondents were asked to answer the questionnaire qualitatively and were additionally free to answer questions freely. The survey was divided into four sections as we have seen in the survey of industry companies. The first section was used to collect the data regarding the respondents' affiliation, these were analyzed only qualitatively. The second section was used to find out whether or not the students already had experience with digital labs. Based on this, the survey was divided into section 3, for the students who have previous experience with digital labs, and section 4, for those who have no previous experience. Section 3 asked how students became aware of digital labs, what lab typology was used and how lab access was, problems encountered during lab use, whether they benefited from the lab and were satisfied. Finally, the survey asked who should pay to use such labs, what payment method was used, and how much students would be willing to pay for a lab supplier in the field of study that would enhance the learning experience. In section 4, lab typology interest was first asked followed by, factors that discourage use and what requirements users have, meaningfulness within the field of study, and general potential of digital labs. Finally, this area also asked who should pay for the use of such labs, which payment method is preferred, and how much students are willing to pay for a lab supplier in the field of study that would improve the learning experience. The survey was not geographically limited, but German and Italian students were actively contacted. 93 students participated in the survey (43% female), of which 85% were between 20 and 25 years old and 13% between 25 and 35 years old. 4% of the students achieved a Master's degree, 20% a Bachelor's degree and 74% a secondary school degree, of which 50% were in the field of professions and applied sciences, 35% in formal sciences, 9% in humanities and social science and 6% in natural sciences. 55% of the students were already aware of digital labs before our survey, and 12% of them used digital labs in their academic curriculum/practices. The results from the section of students who already used digital labs (section 3) are derived from 11 responses. This became aware of the labs mainly through digital channels, which is in line with the findings of the pre-evaluation. Two of the participants already use a marketplace platform to access the digital labs, 6 use access through the university and/or an associated learning management program, and the rest use direct access. Of these, the majority had a problem accessing or using the lab. All students derived some benefit from using the labs and platform. Both the access, problems, and high benefits give a positive indication of the willingness, potential, and usage of a marketplace platform for digital labs. Positively surprising was the feedback from the experienced students about the amount they are willing to pay for a digital lab supplier. Under the clear condition of added value (accessibility and content) for the learning experience, only one student was not willing to pay for the usage, but willing indirectly through tuition fees. All others were willing to pay between 5€ and 50€ monthly or 10€ to 100€ one time. One of the participants was even experienced and had already paid 20€ for the use of a digital lab. The results from the area of students who have not used a digital lab (section 4) are derived from 82 responses. As expectations of the digital labs, they name valuable contents (70%), easiness of use (67%), affordability (48%), materials and equipment not otherwise accessible (59%) and customer care (39%). This describes the requirements or value proposition needed for a successful marketplace platform. In general, 35% find digital labs very helpful to get new information and knowledge and 56% find them helpful, which confirms the demand for digital labs. The feedback on who should pay for the lab use is diverse and controversial. The majority expects universities to pay (54%), followed by the government (35%), students (6%), and the rest from a mix. As a payment method, the majority expects a subscription model. Finally, feedback from students on the amount they are willing to pay for a digital lab supplier. Again, the expected benefit and the needed value proposition is always brought up. There must be a "true value", it depends on the "type of service", it "depends on the content and the amount of service". The students are willing to pay between 10€ and 50€ monthly or 5€ to 100€ one time, with the majority at about 10€ monthly. Compared to the students who already have experience with the digital labs, it is noticeable that those who have no experience find it difficult to assess the benefits (*"I don't know"* or *"I have not any method of comparison"*). Or it should be a mix between university, faculty, and tuition. One feedback states *"it should be part of the educational offer of a university"* another it should be a *"modest amount, not excessive"*, both once again focusing on the educational industry we are in and its expectations such as fairness towards a professional online marketplace.

2.6 Discussion

The established business model for digital labs, as DSRM artifact, is discussed in this section in relation to the research questions, taking into account the literature, the case study, and the evaluation results. The theoretical analysis of the business model has shown that there is still considerable controversy as the core elements are still being investigated. By applying the theoretical construct, it is possible to summarize which functional requirements of the business model are particularly important. The BMD could provide good insight into the components and how value is created, delivered, and captured. The visualization and interaction that was missing could be well supplemented by the BMC. In addition, the Platform Canvas helped to highlight the relationships, functions, and issues between the elements. In particular, it identified the individual value contribution of the actors and the ways to monetize it. Thus, elements such as the value proposition are repeated, but support the holistic and structured technical design of the model. An unsolved problem is that the market situation is dynamic and may necessitate permanent adjustments to the model. The BMC is by nature a static model, which does not mean that it should not be updated regularly and that there are no risks in implementing it. Therefore, as an organizational measure, BMI should regularly question how value is created, delivered, and captured in the marketplace. Subsequent evaluation has also revealed additional insights into the functional requirements. Customers expect valuable content, ease of use, affordable service, access to otherwise inaccessible materials and equipment, and customer support. Simply put, the benefits of a platform must be proven over direct access, and the actual benefits are the selling point. In addition, the system and platform must be trustworthy. This point relates to both the platform's functional and success criteria. However, it is also clear that the two user groups, industry and students, have somewhat different requirements. For example, integration into the corporate structure, data security or the retention of intellectual property are of high importance. For students, the added value must be evident in comparison to or in addition to the regular lecture.

Key answers to the success criteria for a sustainable business model of digital labs were found during the literature review, and further insights were gained through the practical application towards digital labs and evaluation. Sustainable business models are a controversial topic of research and the definition changes according to the person. Modern abstractions refer to ecological, economic, and social aspects. In the context of this work, the authors have considered sustainability in the sense of modern economics as the life span of products, whereby the social and ecological aspects also gain importance here. A multi-sided platform as a marketplace for digital labs reduces the transaction costs to a reasonable minimum. The scalable requirements of a multi-sided platform could be met by digital labs and fit to the scalable BMT. The cross-side networking effect is fulfilled by the lab supplier and buyer sides. Three challenges were identified–development of offerings, acquisition of new user groups, and strengthening user trust. The multi-sided platform helped to respond to the specific demands of suppliers and buyers and provided insight into the necessary trust relationship the network organization requires. The multi-sided platform as a business model has helped to create sustainability and high quality through market balance; the supplier is motivated to offer the highest possible quality. In addition, the directly addressed stakeholder value proposition, the cross-side network effect, the trusted community, the service framework, and the continuous review process based on BMI could be seen as key components of a successful and sustainable ecosystem. Accordingly, a business model develops over several phases with different degrees of innovation. In each phase, strategic direction is required, such as competitive advantage, improvement, or renewal of the business model through innovation, improvement of competitiveness, and an increase in business performance (Julio E. Cuc & Miina, 2018). This need also became clear in the evaluation; the business model should be dynamic, responsive and adaptable to new trends. The experience from the Serious Game also showed that the number of customers' needs to be increased dramatically and that primarily digital sales channels should be used. The results also indicated that digital labs are currently not widely used in industry and are becoming increasingly important in education. Digital labs are seen as very useful for teaching and training. Important for sustainability is the revenue stream, which was evaluated in detail. The majority of respondents see a paid service as useful, provided there is "real added value." A positive surprise was the feedback to pay an amount for a digital lab provider. What also became clear, however, is that a marketplace provider must offer the customer clear benefits, such as easier usability, support, accelerate processes and make services easier to identify. One ethical discussion that is affected by this is who should pay for the course content (university, state, or student). But again, this needs to be considered in context and in relation to the benefits. Finally, industry respondents also indicated a willingness to share labs in the network, which is a good indicator of the sustainability of the offering.

A further finding which needs to be addressed is trust. Trust is addressed several times during this paper and is understood as the success component. Establishing trust in a platform is, as shown, not an easy task and must be at the heart of every element. Today, evaluation systems for the quality and reliability of the transaction partners (Schallmo et al., 2017) and provider protection (verification of users or insurance) are used. The authors believe that a wide-ranging system should be introduced. On one hand, lab environments are very costly, and on the other hand important transactions (lectures) depend on reliability. A trust mode, in which each transaction is evaluated as being above, equal or below expectations, with far-reaching evaluation dimensions and an appropriate visualization system would help to solve this problem. Within logistics processes, performance indicators such as reliability, responsiveness, agility, costs, and asset management efficiency are used to evaluate transactions (APICS, 2017). Social network analysis, for example, could be used as a visualization system to identify key players in a network at an early stage and, if necessary, to initiate measures to ensure the sustainability of the network.

Finally, to give another perspective, a different approach of a feasibility study is discussed. A publicly funded feasibility study (Schmid et al., 2018) in Germany evaluated the use of an (inter)national education platform for higher education and lifelong learning. The goal is similar to what we addressed in this paper, to create a platform for online education and academic learning. Generally, it is assumed that the demand for online education is constantly growing and that students are willing to pay for the education platform. However, the approach does not pursue the transfer of practical knowledge through labs, as explained in this paper. The exciting thing is that a classical business model is used for the feasibility of the university platform. In direct comparison to the innovative and sustainable multi-sided platform, the classic model differs in (1) creating teaching and learning content, (2) the financing model and (3) the staffing requirements. (1) Teaching and learning content is created in-house and requires the development, maintenance and updating of the content and the licensing of the content. (2) The model calculation is based on a financing requirement of 44.5 million euros over six years, with the financing requirement being covered from the seventh year onwards. (3) The staff planning anticipates an increase to 127 internal employees and 670 external tutors/lecturers by the sixth year. This feasibility study shows the advantages of the sharing economy and the benefits of a multi-sided platform as a business model for digital labs. The lab supplier provides the content itself in the best possible way and in relation to the demands of the buyer; the marketplace itself only has a supportive/advisory role. Furthermore, the business model supports the scaling effect for the user. The financial requirements of the marketplace are much lower, as it is possible to concentrate on core competencies. Platform, organizational and operating costs are comparable, but the internal and external staffing requirements are significantly lower.

2.7 Conclusion and Outlook

This paper has addressed the problem of online education for STEM subjects. Lab exercises to gain practical experience and hands-on knowledge play an important role in the education of future engineers and scientists. Digital labs can be used to gain this experience online. However, the sharing of digital labs is currently still insufficient. This paper addresses this problem using DSRM process model in which a multi-sided platform for online exchange of digital labs between suppliers and buyers was established as an artifact. A literature review was conducted to design and develop the success criteria for a sustainable business model and to create a multi-sided platform for digital labs. The literature review included BMD, BMFs, BMTs, and multi-sided platforms. The analysis of the BMD could provide information on whether a definition is necessary and which components are required for a BMD. It can be summarized that a research-related BMD is required and in addition the functionalist view of a BMF should be established. The literature on BMFs helped to identify the different approaches to represent the relationship/hierarchical structure between the elements. For a platform model, it also turned out that the Platform Canvas is the right complement for the BMC. The functionalist view of the business models is combined in the BMT. In these, the scaling property of the multi-sided platform was found to be a criterion for the sustainability of the digital lab business model. The multi-sided platform is tailored to the needs and sustainability of the buyer and the supplier. Based on the theoretical construct, the findings of the literature were demonstrated towards a case study for lab sharing. For this purpose, the feasibility of the concept for digital labs was first examined. Subsequently, the business model was defined and the functionalist view was elaborated. The functionalist view comprises the Platform Canvas and the BMC. Three evaluations were then conducted to evaluate the established DSRM artifact. First, experiences from the serious game industry were compared with those of the labs on the supplier side. Next, 21 industry respondents and 93 students were surveyed about their intentions to use a digital labs platform. The findings from literature, practical experience and evaluation were then discussed in terms of success criteria for a sustainable business model and functional requirements for a multi-sided platform for digital labs. The concept proved to be coherent and targeted. The next step is to put it into practice to gain knowledge and experience. This will provide more detailed insight into the community, further elaborate buyer and supplier demand, clarify dependencies more precisely, and put the network of trust to the test. In addition, experience will be gained from later life cycle phases (dynamic and performance) of the multi-sided platform.

2.8 Acknowledgements

This work has been funded by the Federal Ministry of Education and Research (BMBF), Germany under the funding code 16DHB2112. The responsibility for the content of this publication lies with the authors.

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Chapter 3

3 Paper 2: Interpersonal and Technology-based Trust Research: Gaps and Opportunities for Research and Practice

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Abstract: Trust is something we encounter every day in our personal lives, but it becomes increasingly important in technology-based transactions because traditional interpersonal trust factors cannot be applied as usual. The last "special issue" on trust in the IS research literature appeared in 2008. Given the lead time associated with published research, the studies that were reported in that special issue occurred just prior to the introduction of the first iPhone, when Facebook was in its infancy, and several years prior to the introduction of digital currency or AI-based assistants such as Siri and Alexa. Much has changed since then. A comprehensive review of trust research, from both a non-technology and a technology perspective, provides an opportunity to identify gaps and opportunities for research and practice. Because trust is a very complex construct, we first review the history of non-technology-based trust. This review is organized in the context of personal, professional, and organizational relationships, looking at initial trust and the long-term evolution of trust. Next, an overview of existing technology-based trust studies in the information systems research literature is provided. Finally, we identify where research and practical gaps and opportunities exist for future technology-based trust studies by balancing acquired and practical relevance.

Keywords: Technology-based trust, Interpersonal trust, Initial trust, Long-term relationship, Information systems

3.1 Introduction

All transactions involve some degree of trust. We trust reliable editors of online encyclopedias to ensure accuracy in the online content, that ordered goods will be delivered as expected, that the weather will be as predicted, that a navigation system guides us to our destination, or that our privacy is respected by intelligent personal assistants like SIRI or ALEXA. Trust is a complex construct, such that even when the weather is not as predicted we do not lose trust in the entire prediction model. In contrast, we may not trust the data security of a foreign country's companies even though we have no experience to the contrary. We trust in people, organizations and roles, governments and even in religions, societies, and cultures. And we trust them to fulfill their obligations and to put those obligations ahead of their own immediate interests or expected benefits (Barber, 1987).

> *"If the people cannot trust their government to do the job for which it exists - to protect them and to promote their common welfare - all else is lost"* Barack Obama, 2006.

All else is lost - as the quote makes clear, trust is a fundamental component of our coexistence.

Technology has become another fundamental component of our coexistence. When we speak of trust in technology, we have at least two connotations. First, we trust the technology to operate as it is expected to operate. We trust our mobile banking transactions to execute properly. We trust the technology used in hospitals, homes, businesses, and automobiles to operate properly. Indeed, we trust many technologies with our lives. Second, we trust the technology in various contexts to be used properly. That is, we trust that the bank will properly credit our online bank accounts with a mobile deposit. We trust that the vendor who operates an e-commerce site will deliver the merchandise we have purchased.

Research in trust as a construct began over seventy years ago, but the technology-oriented research in trust is a more recent phenomenon. This paper examines the rich history of non-technology-oriented research of trust to assess existing technology-oriented trust studies and to inform the design and execution of future technology-oriented studies. One paper could never review every non-technological study on trust. Due to the very large number of studies published in the non-technology literature, we limited our review to forty-six papers including seminal papers and papers from a range of disciplines (e.g., business ethics, economics, management, and law, among others). Due to the rapid change in technology and the emergence of the networked world since the mid-1990's, we also limited our review of technology-based trust research to twenty-six papers published in well-recognized information systems research journals (e.g., *European Journal of Information Systems*, *Journal of MIS*, *MIS Quarterly*, and *Information Systems Research*, among others) and at IS research-oriented conferences since 2000. As technology becomes more and more ubiquitous in our lives, we need to understand how trust in technology and in the use of technology is created, maintained, destroyed, and possibly rebuilt. This knowledge is important for the developers of technology, in order to create successful technology uses, and for the users of technology, in order to be aware of the vulnerabilities and potential risks of technology use.

3.2 Interpersonal Trust

An overview of the general context of trust, the definition, a delimitation and the fields of research is given. The social context of trust, particularly in personal, professional, and organizational relationships, is then provided. For trust to develop between individuals and organizations, they must encounter each other repeatedly, and have some memory of previous experiences (Williamson, 1993). Therefore, the development of a long-term trust relationship is then described and concludes with the paradoxical nature of trust, in each case without consideration of technology.

3.2.1 General Context of Trust

Trust arises from relationships, therefore it can be created and destroyed (Flores & Solomon, 1998). In a trust relationship, two parties are involved, there is uncertainty and risk, and the trustor has confidence in the honesty and benevolence of the trustee (Siau & Shen, 2003). A distinction is made between weak and strong trust relationships; a strong one characterizes that we feel secure and trust that our partner can rely on us and responds to our needs (Rempel et al., 2001). However, we say someone is trustworthy, meaning we have an appreciative evaluative appraisal towards an exchange partner (person or organization) who does not exploit our vulnerabilities (Brenkert, 1998; Cowart et al., 2014).

Trust is based on various trust factors, is built on the basis of reliability, predictability, and fairness in accumulated experiences (Zaheer et al., 1998), and can be influenced by recommendations from confidants (Ba et al., 2003). However, trust relationships can also be fraught with ethical pitfalls and can be exploited, as the trust relationship is limited by the fact that the best interests of the trustor are determined by the trustor and not the trustee (Husted, 1998).

However, in the absence of accumulated experience, how can we trust? Without trust, people would be faced with the unmanageable complexity of considering every possible contingency of every person in the environment before deciding what to do (Gefen, 2000). We see trust is a complex construct but one that is an essential ingredient and ubiquitous in business and society.

In 1958 Deutsch defined trust and distinguished it from mistrust. Since then, trust has been defined in many ways. "*An individual may be said to have trust in the occurrence of an event if he expects its occurrence and his expectation leads to behavior which he perceives to have greater negative motivational consequences if the expectation is not confirmed than positive motivational consequences if it is confirmed*" (Deutsch, 1958, p. 267). Authors have expanded the individual in Deutsch's work to be an actor, corporation, or community in which fiduciary obligations and responsibilities are assigned (Barber, 1987; Fukuyama, 1995; Zaheer et al., 1998). Trust is the expectation, confidence, probability, predictable manner, or willingness (Brenkert, 1998; Rempel et al., 1985) of others on whose goodwill one depends that an event, task, or action will be performed (Barber, 1987; Soule, 1998). Trust is a product of our relationships, it is on the one hand the credibility, goodwill or gratification towards others, while feeling vulnerable or taking a risk (Doney & Cannon, 1997; Friedman et al., 2000; Lewicki & Bunker, 1995) and on the other hand a (subjective) deviation between positive and negative consequences or even opportunism (Flores & Solomon, 1998; Williamson, 1993). Some indicate that trust is based on commonly shared norms, a social practice, a social relationship, or ethical behavior (Fukuyama, 1995; Gefen, 2000; S. P. Shapiro, 1987). Trust is a complex and multidimensional construct which makes it difficult to operationalize (Simpson, 2007), observe, interpret, and measure (Gulati, 1995).

While building an understanding of trust over the years, researchers have also clarified what trust is not. Trust is not related to academic success or achievement (Rotter 1980), nor is it necessarily the same as morality or moral action (Brenkert, 1998), and trust, of course, does not really enable people to control the behavior of others or even to predict it without error (Gefen, 2000). Nor is distrust a lower level of trust, but its opposite, a separate construct based on different emotions than trust (D. Harrison McKnight et al., 2002b). As the variety and emphasis of definitions indicates, the concept of trust varies depending on the focus of a study (D. H. McKnight & Chervany, 1996).

Trust has been extensively studied in psychology, sociology, and philosophy to examine its influence on personal behavior, social order, and social behavior. Additionally, research on trust has occurred in areas of professional ethics, examining topics such as ethical behavior in business, science, leadership or management and its influence on trust and also in relation to law. Another major field of research is trust in economics, the most prominent example being the role of trust in transaction costs (Williamson, 1993) or trust as exemplified by the prisoner's dilemma (Deutsch, 1958). Trust in economics examines trust between and within organizations, in leadership or management, and in a corporation's like alliances. More specialized research has led to deeper examinations of trust in narrower areas, such as trust as a marketing instrument or as a basis for information systems. As a marketing instrument it is studied for brand equity, brand identity and brand personality to increase revenue. In general, economic theory continues to apply, or rather, support the idea that all behavior is driven by the market. Granovetter (1985) claims that relational ideas such as trust are rendered as unneeded in the model, since buyers simply move on to other sellers in cases of distrust or misbehavior. This idea is countered by salespeople who depend on the social context of trust to cultivate customer loyalty in business relationships.

3.2.2 The Social Context of Trust

Trust occurs in various social contexts. Trust can arise between persons as well as between persons and organizations as mixed forms. The conditions for interpersonal and interorganizational trust are related, but are distinct constructs and play different roles in affecting exchange performance (Zaheer et al., 1998). Furthermore, a distinction is made between a trust relationship that is already established on the basis of an existing trust relationship and a trust that must be established first. We distinguish between three trust situations. 1) The personal relationship which includes the initial trust situation, person A does not have a trust relationship or does not make a trust evaluation to/from person B, and subsequently the situation occurs that person A trusts person B. These are also determined by individual characteristics. 2) The professional relationship, in which a person trusts an organization, institution, or a professional role. 3) The organizational relationship, in which trust is established between two companies. We also briefly discuss international and cultural relationships.

3.2.2.1 Personal Relationship

The starting situation is trust in an unknown person. Trusting a stranger is not blind trust, but simple trust is a naïve, still unquestioned trust that is free of mistrust (Flores & Solomon, 1998). When you trust someone who you do not know (have no prior relationship with), you communicate to the person that you think favorably of them. Like any investment, it may have a risky side, as the trustee may not be required to act as expected (Pettit, 1995). If that person values a good reputation, the person is likely (positive motive) to think about it before letting the trustor down. If the person abandons the trustor, the trustee loses the good opinion that the trustor has shown or promised, and he also loses the good opinion that the trustor may have gained for himself with (other) third parties (Pettit, 1995).

The perhaps best-known relation is the trust relationship between two people called interpersonal trust, on which no organizational form finds direct influence, and which is strongly represented in psychological trust research. When individuals are socially closer, both trust and trustworthiness increase (Glaeser et al., 2000). Simpson (2007) proves that the belief that the participants' self-interests are aligned and the belief that the partner is interested in the relationship increases trust.

Within the domain of interpersonal trust, researchers have studied romantic and non-romantic relationships. In a study of romantic relationships by Boon and Holmes (1991), it is described that a romantic relationship goes through three stages of development, the romantic stage, the evaluative stage, and then the accommodative stage (Lewicki & Bunker, 1995, 1996). In this process, the parties exhibit fundamentally different behaviors and dynamics of trust. In the romantic stage, trust and love tend to be undifferentiated. Hope outweighs fear that the relationship may not work. In the evaluation stage, genuine trust develops. Through mutual disclosure of thoughts and feelings, the parties take a risk and evaluate the relationship. The third accommodative stage solidifies trust; a leap of faith is made to withstand threats of major individual characteristics that influence trust, such as differences or incompatibilities. This stage is characterized by negotiation of needs, expectations, and incompatibilities.

In the study of social trust outside of romantic relationships, when we say that person A trusts person B to do something, we usually imply that B is aware of A's trust (Deutsch, 1958). In contrast, mutual trust is when A and B have complementary social trust regarding each other's behavior and both are aware of it (Deutsch, 1958). In general, interpersonal trust is defined as an expectancy held by an individual or a group that the word, promise, verbal, or written statement of another individual or group can be relied on (Rotter, 1971). Flores and Solomon (1998) describe this as a mutually affected dynamic, and Rempel et al. (1985) describe it as dyadic trust when it is benevolent and honest. Four core principles of interpersonal trust emerge in the literature (Simpson, 2007): individuals measure the degree of trust by observing how partners behave in trust-diagnostic situations; trust-diagnostic situations often occur naturally and unintentionally; individual differences influence trust growth over time in relationships; neither the level nor trajectory of trust in relationships can be understood only through the dispositions and actions of both relationship partners. Deutsch (1958, 1960) investigated that interpersonal trust is promoted by (1) knowing how the other person will perform, (2) a co-operative orientation, (3) communication, and (4) a disliked third person. In contrast, a competitive orientation inhibits trust. The influence of the person's background on trust has also been studied by various authors. Trustworthiness decreases when partners belong to a different race or nationality (Glaeser et al., 2000), also within society, rules or habits, common norms and moral values have an influence on trust (Fukuyama, 1995; Husted, 1998). A high level of trust requires conditions that include motives, consistency, competence, and openness (Brenkert, 1998) and a willingness to disclose personal information (Rotter, 1971).

Individual characteristics also influence trust. Deutsch (1958) found that trusting individuals are more likely to be trustworthy and suspicious individuals are more likely to be untrustworthy. Trust itself is influenced by people's disposition to trust and by familiarity (Gefen, 2000). Rotter (1971, 1980) identified several conditions of parents that positively influence trust, such as parents' religiosity, father's trust score, parents' trust of outsiders, parents' who taught trust and trustworthiness, and negatively, such as expectancies, dependence on others, locus of control, and arrogance. Rotter also defined characteristics of high trusters as social desirability, truthful, better *"adjusted"*, and less likely to abandon instructions, invade privacy, cheat and steal. On the other hand, low self-esteem and uncertainty reduce trust. Sorrentino et al. (1995) also provide evidence for the certainty orientation, according to which insecure individuals tend to have moderate trust in a partner, whereas certainty-oriented individuals have high or low trust in a partner, but not moderate trust.

3.2.2.2 Professional Relationship

The professional trust relationship includes several situations. In one case, the person knows the organization and trust is considered by the example of a brand. The next situation is about trust and expectations in an institution. Thirdly, trust may occur in a professional role, such as a colleague or supervisor, cab driver, or knowledgeable person. In contrast to personal relationships, trust in professional relationships does not begin with the development of intense emotionality (Lewicki & Bunker, 1996).

The trust relationship between a person and an organization is studied in context of brands and marketing research. Basically, trust influences both intended inquiry and intended purchase (Gefen, 2000). Trust reduces uncertainty in an environment where consumers feel particularly vulnerable because they know they can rely on the trusted brand (Chaudhuri & Holbrook, 2001; Huff & Kelley, 2003). Researchers have determined that a brand is much more than a product. Chaudhuri and Holbrook (2001, p. 82) define brand trust as *“the willingness of the average consumer to rely on the brand's ability to perform its stated function”*. A brand is a value proposition or a customer relationship based on the associations of the organization, credibility for the brand, and a vehicle for the culture and values within the organization (D. A. Aaker, 1996). Trust, which is often part of a corporate brand's core identity, provides a strong foundation for the relationship between an organization and its customers. Brand personality is the set of human characteristics associated with a brand (J. L. Aaker, 1997). A trustworthy organization is perceived as honest in its communication and dealings with customers, and is reliable and sensitive to customers' needs (J. L. Aaker, 1997). Chaudhuri and Holbrook (2001) found that brand scores represent the average response potential of the brand in terms of the trust, affect, or loyalty it elicits from consumers, and that brand trust affects attitude loyalty and purchase loyalty.

Husted examined the situation of trust in institutions such as the state, the health care system, legal insurance, professional associations and the public media (Husted, 1998). In institutional trust, we are persuaded by the social and organizational context (Williamson, 1993), the structural assurances, and situational normality (D. Harrison McKnight et al., 1998). As described in the opening quote, we expect a state to be a reliable and trustworthy partner that protects its citizens and their commonwealth in times of environmental disasters, war, or pandemics. Institutional trust underwrites interpersonal trust. If trust in our common institutions erodes, trust in other people will also be lost (Lewis & Weigert, 1985b). As an example from the justice system, we expect the administration of justice to be based on procedural justice, the so-called justice-based trust. Procedural justice is concerned with the effect of decision-making processes on the fairness perceptions of those who are affected by decisions - the trusted party (Husted, 1998).

Trust in people based on their professional role and organizational affiliation is driven by social norms, such as how we trust co-workers, how we trust a stranger, or how the cab driver decides whether to take a passenger (i.e., trusts that a potential passenger is not a threat). We trust knowledgeable professionals based on their expected competencies and institutions based on the social and organizational context.

What is known as internal trust is formed between co-workers or acquaintances. It is the climate of trust within an organization associated as positive expectations toward organizational members regarding intentions and behaviors based on organizational roles, relationships, experiences, and interdependencies (Huff & Kelley, 2003). In addition to internal trust, swift trust can also occur when members are trusted in a new project, not because of past experience, but because of their background, professional credentials, and affiliations (Kanawattanachai & Yoo, 2002). High-performing teams are better able to develop and maintain a level of trust, with identical baseline levels of trust in the cognitive and affective dimensions (Kanawattanachai & Yoo, 2002). Virtual teams rely more on a cognitive than an affective level of trust (Kanawattanachai & Yoo, 2002). In addition to trust between peers, trust in superiors and subordinates is based on integrity, competence, consistency, loyalty, and openness (Butler & Cantrell, 1984). In this context of leadership, a distinction is made between relationship-based trust, which refers to the principles of social exchange between manager and employee, and character-based trust, which can refer to the character of a manager's employee in a hierarchical relationship (Cowart et al., 2014). Furthermore, the characteristics of trustworthy managers have also been examined. Trustworthy managers are ethical, have a positive impact on culture, promote employee growth and development, treat employees fairly and consistently, promote work-life balance (Gordon et al., 2014), demonstrate personal commitment, and are characterized by employee loyalty, and job satisfaction through perceptions of effectiveness (Cowart et al., 2014). Employee trust in leadership is reflected in organizational performance, improvement in problem solving, communication, negotiation, performance, organizational commitment, and levels of employee turnover. In contrast, trust in leadership is said to be lacking when a shared sense of value and purpose between employees and leaders does not exist which can lead to an increase in workplace conflict (Cowart et al., 2014).

With a knowledgeable person and a cab driver, other criteria come into play. In the case of a cab drivers, characteristic-based trust arises. Cab drivers do not know anything specific about a potential passenger since no previous experience with that person is known. They must make their decision whether to stop based on what they can infer from the setting. In this case, trust consists of an actor offering a definition of itself to an audience that chooses either to interact with it (trust) or not to interact with it (distrust) (Williamson, 1993).

Trust in a knowledgeable person and their capabilities is something we frequently encounter in everyday life (Doney & Cannon, 1997). People with high status are able to elicit more trustworthiness from others (Glaeser et al., 2000). Professionals such as doctors, lawyers, or university professors are expected to have a high degree of judgment and initiative because they have had several years of technical education in a field (Fukuyama, 1995). For example, a qualified scientist is expected to be trusted to observe the moral norms of science, to fulfill their normative obligations to their immediate colleagues, the broader scientific community, and the public, as well as to the particular institution in which they work and that a scientist does not exploit the absolute autonomy of science (Barber, 1987).

3.2.2.3 Organizational Relationship

Trust due to organizational affiliation is described as the extent to which organizational members have a collectively held trust orientation to a partner firm (Huff & Kelley, 2003). Interpersonal and interorganizational trust have been shown to be highly correlated but distinct constructs, as identified by Zaheer et al. (1998), that play different roles in influencing exchange performance. Because it permeates both, trust cannot be fully understood and studied exclusively at the psychological or organizational level (Lewis & Weigert, 1985b). Zaheer et al. (1998) argue that organizational trust has its basis in individuals. It is the individual members of organizations, rather than the organizations themselves, who trust (Huff & Kelley, 2003). Organizational trust occurs when individuals generalize their personal trust to large organizations composed of individuals with whom they have little familiarity (Lewicki & Bunker, 1995). The institutionalization of a relationship is based on three interactions that develop over time according to Ring and van de Ven (1994): (1) personal relationships increasingly complement formal role relationships, (2) psychological contracts increasingly replace formal legal contracts, and (3) formal agreements increasingly reflect informal understandings and commitments. According to Aaker (1996), an organization is trusted and believed when it makes claims, is seen as honest in communication, and is perceived as reliable and sensitive in dealing with customers. In addition, trust leads to commitment in the exchange of business-to-business relationships (Chaudhuri & Holbrook, 2001). Interorganizational trust is defined as "*the extent of trust that members of a focal organization place in the partner organization*" (Zaheer et al., 1998, p. 142). Williamson (1993, p. 486) examines the economic impact of trust and further states that "*institutional trust refers to the social and organizational context in which contracts are embedded*".

Further studies deepen the idea of contracts and trust between organizations to counter opportunistic behavior. The concept of calculus-based trust (or calculative trust) describes the market-oriented, economic calculation whose value is derived with the cost of maintaining or breaking the business relationship (Lewicki & Bunker, 1995). Interorganizational trust, on the other hand, functions as a governance mechanism to mitigate opportunism in exchange contexts characterized by uncertainty and dependence (Doney & Cannon, 1997). Transaction cost theory also stems from this idea. Greater trust in other parties lowers the transaction costs (time and expenditure) which are needed to negotiate, reach agreements and contracts, or to accomplish a cooperative interorganizational relationship (Williamson, 1993). In doing so, management flexibility increases (Ring & Van de Ven, 1994). Thus, trust can be used in business transactions as a complement to, or even a substitute for, formal legal contracts to counteract fraud and thus affects calculus-based trust (Anderson & Weitz, 1989; D. L. Shapiro et al., 1992). Increasing trust between parties also increases the likelihood that parties will be willing to make larger and riskier investments in future transactions (Ring & Van de Ven, 1994). In summary, interorganizational trust emerges as an overall driver of exchange performance, negotiations, and conflict, while interpersonal trust exerts little direct influence on these outcomes (Zaheer et al., 1998). On the other hand, there is what is known as deterrence-based trust (which is also associated with calculus-based trust), which can exert indirect influence on interorganizational trust. Deterrence-based trust occurs when the potential costs, penalties, or likelihood of retaliation if the relationship is broken outweigh the short-term benefits of opportunistic behavior (Gulati, 1995; D. L. Shapiro et al., 1992).

In an agent-client relationship, trust is more basic because of the skill gap that exists between the two parties (Lewis & Weigert, 1985a). In contrast, in an agent-agent relationship, trust is more diverse. As an example, Doney and Cannon (1997) studied the trust relationship of a sales person of a supplier organization to a buyer organization. They found that trust in a supplier company is positively related to the likelihood that buyers plan to do business with suppliers in the future (Doney & Cannon, 1997). According to the results, trust of the seller as an agent can be transferred to the supplier firm and vice versa (Doney & Cannon, 1997). A high level of trust allows the parties to focus on the long-term benefits of the relationship. Zucker (1986) and Husted (1998) described the so-called process-based trust which is reflected here as a long-term pattern of exchange between the bound parties. In a supply chain relationship, trust corrects short-term inequities to achieve long-term benefits (Anderson & Weitz, 1989). Trust determinants thereby are reputation, support, goal congruence, cultural similarity, age, communication, and power imbalance (Anderson & Weitz, 1989). Similarly, alliances depend on the trust that develops between organizations over time through repeated connections (Gulati, 1995).

3.2.2.4 International and Cultural Relationship

International and cross-cultural relationships are determined by further factors such as personal relationships or cultural background, which also promote trust (Brenkert, 1998). Cultural background affects trust, as the level of individual and organizational trust varies across cultures (Huff & Kelley, 2003). Trust is determined by the level of trust inherent in society (Fukuyama, 1995). A society with high trust, such as Japan, Germany, and the United States, may organize its workplace to be more flexible and group-oriented, delegating more responsibility to lower levels of the organization (Fukuyama, 1995). Low-trust societies, on the other hand, such as China and southern Italy, must fence in and isolate their employees with a bureaucratic set of rules and contracts (Fukuyama, 1995). Consequently, collectivist cultures are better at fostering trust than individualistic cultures, especially toward external partners (Huff & Kelley, 2003). Accordingly, it is difficult to find and control the right level of trust and rules in cross-cultural organizations or business relationships. The wrong level of trust can suppress or, on the contrary, overwhelm individuals.

3.2.3 The Development of a Long-Term Relationship of Trust

Besides initial trust, there are different trust models that reflect the evolution of trust during the parties' interaction. Lewicki and Bunker's (1996) model of the transitional stages of trust development, in which two parties enter into and develop a new relationship, is one of the most complete because it explains how trust and relationships change, develop or decline over time, and how trust can be restored. It draws on the framework of Shapiro et al. (1992) and Lewicki and Bunker (1995). The model of transitional stages in trust consists of three types of trust linked in a sequential iteration in which the achievement of trust at one stage enables the development of trust at the next stage. The three transitional stages of calculus-based trust, knowledge-based trust, and identification-based trust have a hierarchical relationship, and each basis entails different benefits and different costs (Lewicki & Bunker, 1995, 1996; D. L. Shapiro et al., 1992). However, not every relationship develops at the highest level, so trust may stagnate, decline, or for a few, rise to the next level. According to Lewicki and Bunker (1996) the evolution from one stage to the next requires a "*frame change*", a fundamental change in the prevailing paradigm of perception.

The first stage is calculus-based trust. As introduced before, calculus-based trust refers on the one hand to the aforementioned deterrence-based trust, the fear of punishment for violating trust, but on the other hand also to the rewards of relationship preservation (Lewicki & Bunker, 1996). Calculus-based trust is an ongoing, market-oriented, economic calculation whose value is derived from the outcomes of a relationship that result from its creation and maintenance relative to the costs of maintaining or servicing it (Ba et al., 2003). If building trust is a slow, forward moving process, then breaking trust can set a relationship back, or throw it right back to the starting position.

The second stage is knowledge-based trust. This trust type is grounded in the predictability of the other, knowing the other sufficiently well so that the other's behavior is predictable (Lewicki & Bunker, 1996). Compared to calculus-based trust, it is based on information rather than deterrence. It develops over time, mainly on the basis of historical interaction that allows actors to develop a generalized expectation that the other's behavior is predictable and that the actors act in a trustworthy manner (Rotter, 1971). The basis for knowledge-based trust is regular communication and courtship; without it, the relationship loses touch (S. P. Shapiro, 1987).

The third stage is identification-based trust, the highest order of trust (Lewicki & Bunker, 1996; S. P. Shapiro, 1987). This is based on identification with the desires and intentions of the other (acting for each other). The parties understand and value each other's desires, and this mutual understanding develops to the point where each can act effectively for the other (Lewicki & Bunker, 1996). It is closely related to the group-based trust that Kramer and Tyler (1996) describe, in which group members identify with the goals supported by particular groups and organizations. Within identification-based trust, one party can serve as a proxy for the other, confident that its interests are fully protected and that no monitoring is necessary (Lewicki & Bunker, 1996). In summary, parties know what needs to be done to sustain the other party's trust and can predict and share some of the other party's needs, choices, and preferences, while, as with knowledge-based trust, they cannot merely know and identify them (Lewicki & Bunker, 1996). Collective identification, colocation, creation of common products or goals, and shared values are cited for identification-based trust as activities that strengthen trust (Lewicki & Bunker, 1996).

On the other hand, trust can be reduced by a one-time disturbance/destruction or by a gradual erosion of trust (Lewicki & Bunker, 1996). In the case of a disruption of mutual trust, there is a cognitive and emotional evaluation of the situation. When confronted with a violation of trust claim, the alleged violator is either guilty as charged, not guilty, or some fundamental disagreement about the relationship is exposed. There are different ways of reacting to this situation. Either the relationship is terminated, the relationship is recalibrated and continued on a different basis, or the relationship is restored on the previous level. A relationship damaged by a violation can be repaired, however, trust repair is a two-way process that occurs differently at each stage. Although a violation of trust is usually committed by one person, a significant amount of work is required by both the violator and the violated to repair the relationship. Both must be willing to invest time and energy, believe that the benefits of gaining the relationship are worth the investment of additional energy, and that the benefits are commensurate with the possibilities of satisfying them in alternative ways (Lewicki & Bunker, 1996).

Besides this model, the initial trust formation model and the risk of trust development model are common. McKnight et al.'s (1998) initial trust formation model is based specifically on beginning trust in a relationship between two parties. The initial trust formation model does not assume any kind of experience with or first-hand knowledge of the other party. Rather, it is based on an individual's disposition to trust or on institutional cues that enable one person to trust another without firsthand knowledge of them. In doing so, they distinguish between the cognitive-based model which is better for the study of initial trust to the knowledge-based model which is better for the study of ongoing trust. The risk of trust development model by Mayer et al. (1995) describes that trustworthiness is perceived through ability, benevolence, and integrity, which leads to propensity to trust. The degree of trust is compared to the degree of perceived risk in a situation, resulting in the risk taking in a relationship. The assessment of risk in a situation includes consideration of context. Risk taking leads to outcomes, which feed into factors of perceived trustworthiness as a feedback loop, a phenomenon he describes as the dynamic nature of trust.

3.2.4 The Paradox Nature of Trust

All of this is accompanied by paradoxical trust phenomena. The biggest paradox is probably that one does not begin to build trust unless some level of trust is assumed, but one does not want to assume trust unless a basis for trust exists (D. L. Shapiro et al., 1992). This implies that exposure to risk is unavoidable and interactions must occur while partners' trustworthiness characteristics are learned (Fullam & Barber, 2006). It is also worth mentioning the paradox that Deutsch (1960) stated that people who are distrustful tend to be untrustworthy and those who trust are trustworthy. Behavior toward the other is congruent with what one expects from the other and vice versa (Deutsch, 1960).

Another paradox is the interplay between trust and economic decisions. Economic theory implies that relational ideas such as trust are not needed because buyers will simply switch to other sellers in cases of distrust or misbehavior (Granovetter, 1985). Trust relationships are fraught with ethical pitfalls and the root of corruption. Husted (1998) argues that an interest in trust is always seen in active tension with economic efficiency and fairness. Active competition seeks to identify and exploit these vulnerabilities (Brenkert, 1998). Finally, there is a trust paradox in virtual cooperation. Participants in a virtual collaboration focus on what they know well, so the components that each individual partner brings to the table are by definition outside the expertise of the other partners (Jones & Bowie, 1998). So trustworthy behavior would be necessary, but this is not in the self-interest of the individual partner (Jones & Bowie, 1998).

Another paradox is the contradiction between rule and trust. Should the constraints on trust be set so tightly that undesirable behavior is prevented, or so flexibly that inappropriate behavior is tolerated? According to Shapiro (1987), in eliminating opportunities to violate trust, trust itself is eliminated, i.e., strict contracts essentially remove the opportunity for trusting behavior. He (S. P. Shapiro, 1987) therefore argues that weak controls are essential to the modern economy. Fukuyama (1995) describes this as an inverse relationship between rules and trust. The more rules people rely on to regulate their interactions, the less they trust each other and vice versa (Fukuyama, 1995). And yet, colloquially, we often say we trust someone or something because of the rules in place. Ring and van de Ven (1994) add that excessive formalization and monitoring leads to conflict and distrust between parties. An example is that professional buyers are trained to focus on objective evidence that demonstrates the superiority of a product offering rather than on subjective assessments of trust (Doney & Cannon, 1997). An order winner is not influenced by trust in the supplier firm or its salesperson.

3.3 Trust Studies Involving Technology

Having reviewed the study of trust in non-technology contexts, we turn now to the study of trust specifically in the context of technology. Notably, we have found only two special issues in information systems journals that were devoted to trust: Special Issue on "*Trust in the Digital Economy*", the Journal of Strategic Information Systems, Volume 11, Issues 3–4 (2002) and Special Issue on "*Trust in Online Environments*", Journal of Management Information Systems, Volume 24, Issue 4 (2008). There has been a smattering of other studies published as well, but the depth of study does not compare to what has occurred outside of the information systems research literature (Janzik & Quandt, 2021).

In the field of information systems, trust is studied to achieve trust in technology for example in online auctions, artificial intelligence, e-commerce or software engineering. Since trust is also the central aspect of e-commerce (Gefen, 2000), many studies have investigated how trust can be built even when personal experience is lacking. The difference with trust online is that it is more difficult in an online situation to reasonably assess the potential harm and good will of others (Friedman et al., 2000), which is also referred to as information asymmetry (Ba et al., 2003). New methods have been created for this purpose, such as a user-centered rating system, trusted third party certifications, or recommendations from confidants. But web technology goes well beyond e-commerce and is an integral part of information systems (Söllner et al., 2016) and our environment. We trust actuators and sensors that collect information to control business processes in the Internet of Things. We trust AI-based digital assistants to give truthful answers to queries and to control our homes in a safe and secure manner. So, what trust approaches can be used in the combination of online activity and technology?

3.3.1 General Trust in Technology Concepts

Friedman et al. (2000) noted trust depends on our ability to perform three types of assessments: the harm we might incur; the good will others have toward us that might affect their efforts to protect us from harm; and whether harm that does occur lies outside the parameters of the trust relationship. In assessing trust in technology, Friedman et al. (2000) observed that people trust people, not technology. Unfortunately, an online environment makes it difficult to assess the potential for harm or goodwill in others. They deemed that technological artifacts (circa 2000) had not yet been produced that warranted any attribution of *"consciousness or agency"*, hence trust is placed in the designers of the technology. However, one's trust in the designer of a technology is limited by one's understanding of the technology – how and when it functions reliably and safely. Often, people are in no position to determine what performance is actually *"reasonable"* for a technology. We can extend this attribution of trust in people over technology to describe that we trust professionals to use technology appropriately and safely. For example, we trust medical technicians to use MRI and other powerful body scanning technology safely.

Friedman et al. (2000) provide other examples of how trust in online environments must be considered in ways that emphasize people over technology. In online transactions, trust violations can occur through loss of money and loss of privacy. In online interpersonal interactions, a violation of trust can leave a person feeling hurt, embarrassed, or psychologically vulnerable.

Friedman et al. (2000) warned that as online interactions became more central to public discourse, we must guard against *"conflating trust with other important aspects of social interaction"*. This is a prescient warning about the darker side of much social media interaction that occurs today. They provide ten trust-related characteristics of online interaction (Friedman et al., 2000): (1) reliability and security of the technology, (2) knowing what people online tend to do, (3) misleading language and images, (4) disagreement about what counts as harm, (5) informed consent, (6) anonymity, (7) accountability, (8) saliency of cues in the online environment, (9) insurance, and (10) performance history and reputation. Notably, only the first item in the list, and possibly the eighth, is grounded in technology. They recommend a *"value-sensitive"* design approach that takes into consideration human values in a *"principled and comprehensive manner"*.

The proposition that trust in online environments has little to do with technology *per se* is supported by reflecting on Gefen's (2000) work. In his study of antecedents to trust in an e-commerce setting, Gefen (2000) notes that it is through interactions with others that people build beliefs about the integrity and intentions of other people (not technology). Familiarity with people in a transaction is needed so that the expectations of trust may be made explicit. As Friedman et al. (2000) noted, familiarity with the (technological) environment is also needed, in that it helps to expand the limits of understanding so that expectations can be set. Familiarity is not trust; it is an antecedent to trust. Familiarity helps to reduce dependence on others and one's own sense of vulnerability. Familiarity helps one understand current actions of people (or technology), while trust deals with future behaviors. Gefen (2000) concluded inquiry (e-commerce site browsing) and intent to purchase were affected by trust and that trust was affected familiarity and disposition to trust (a general inclination to display faith) in an e-commerce environment. These are not technological factors. However, Gefen (2000) also noted (citing others) that trust is "*complex, multi-dimensional, and context-dependent*". Subsequent studies of online environments have certainly confirmed this position.

For example, Belanger et al. (2002) determined consumers rely on their perceptions of trustworthiness irrespective of whether the merchant is electronic only or land and electronic when making the decision to provide private information. They also concluded that privacy and security features (of web sites) were of lesser importance than pleasure features when considering consumers' intention to purchase. Generally, they concluded that consumers did not evaluate the use of trust indices on web sites the way experts assessed them.

Similarly, Pavlou (2002) concluded that independent certifications and legal bonds had no impact on credibility in an online environment. Rather, monitoring activities to ensure transactions were executed as expected, providing opportunities for feedback, and maintaining cooperative norms were factors that impacted the credibility of a website. Feedback and cooperative norms impacted "*benevolence*", which reduced perceived risk and increased continuity (of use). Credibility had a similar impact on perceived risk and continuity and increased satisfaction.

3.3.2 Initial Trust in Online Environments

McKnight et al. (1998) examined initial trust in online environments. A paradox of trust is that one must trust (to some extent) to trust. That is, initial trust between parties is not based on any prior experience or knowledge of the other party. It is based on other cues, such as knowledge of an institution, knowledge of a role played by the party to be trusted (e.g., a police officer), or experience in a prior situation that is deemed similar enough to conclude that some degree of trust is warranted. Citing Gambetta (1988), they note that initial trust is not based so much on evidence as on lack of "*contrary*" evidence [their emphasis]. It seems unlikely that a website would have contrary evidence that affects the cues mentioned earlier. Lowry et al.'s (2008) empirical study bears out McKnight et al.'s (1998) premise. Lowry et al.'s (2008) study identified constructs such as brand image, website quality, disposition to trust, and institution-based trust as factors affect initial trust.

Only website quality in this instance has anything to do with technology. During the same period, Vance et al. (2008) found that trust in the IT artifact was directly influenced by navigational structure and visual appeal. However, they also concluded culture can affect the degree to which users trust a technology artifact. Persons from different cultures perceived IT artifacts differently, influencing intentions to adopt technology. Cyr (2008) confirmed cultural differences related to uncertainty avoidance in finding trust to be more important than satisfaction to "*e-loyalty*" in China, equally important in Germany, and less important in Canada. Well-designed and aesthetically pleasing web site design was important, especially in collectivist (strong uncertainty avoidance) countries (e.g., China). Kim (2008) argues that although the role of trust in e-commerce does not vary across cultures, its determinants do. Cultural differences determine which trust determinants effect consumer trust and how.

3.3.3 Technological Trust Factors

However, research has been conducted to identify what might serve as evidence that initial (and on-going) trust is warranted. Ba et al. (2003) found increasing use of feedback systems, insurance, guarantees, and escrow services as mechanisms to encourage trustworthiness. They discuss the *"trusted third party"*, an agent recognized as an objective evaluator of the trustworthiness of a website. Trusted third party icons, such as a *"seal of approval"* or a designation that the website operates according to an accepted set of standards, play the role of one's trusted friend who recommends or vouches for an otherwise unknown entity. They note that complete information about a website operator is impossible to ever attain, especially in a global environment, but the trusted third party can act to fill the gap in knowledge that a potential website user has.

The trusted third party acts as an *"electronic substitute"* for non-web-based environments. Jøsang et al. (2005) identified two fundamental differences in how trust and reputation are used in online versus traditional environments. First, traditional cues that would be observed in the traditional environment such as body language, facial expressions, and the business environment are missing in online environments. Hence, electronic substitutes are used to provide substitute cues. Second, the communicating environment is potentially global, whereas in a traditional context the communicating environment is more likely to be local. Again, the trusted third party acts to provide information that can fill gaps in local knowledge about a global vendor. Jøsang et al. (2005) discuss trust management in online environments in terms of creating systems and methods that (1) allow parties to assess the potential risk of transactions and (2) allow system owners to accurately represent the reliability of themselves and their systems.

Other studies have approached the study of online / technology trust in different ways. Kim and Benbasat (2006) took an argumentative approach. They studied three scenarios: presenting only claims that users should trust a website; presenting claims and data that users should trust a website; and presenting claims, data, and backing (i.e., argumentative support) that users should trust a website. They found that presenting claims and data increase consumers' trust more than presenting only claims. Further, presenting claims, data, and backing resulted in the greatest increase in trusting belief. Taking a more analytical modeling approach, Tang et al. (2008) asserted that a firm's ability to influence consumer trust depends on the firm's ability to send unambiguous signals that a consumer's privacy will be protected.

More recently, McKnight et al. (2017) have made a comprehensive study of the perception of trust in an online environment. Among the results they report are information quality and system quality impact trusting beliefs; information quality, system quality, and service outcome quality impact distrusting beliefs (all in a negative fashion); trusting beliefs impact relationship commitment; trusting beliefs and distrusting beliefs impact perceived risk (negatively and positively, respectively); relationship commitment and perceived risk impact continuance intention (positively and negatively, respectively).

3.3.4 E-Commerce Trust Studies

Examining e-commerce more specifically, Gefen et al. (2003) emphasized the "*inseparable but complementary*" aspects of e-commerce websites, namely that the technology unites a vendor on the one hand with a customer on the other. Hence, these are the two perspectives to examine: the technological attributes of the website and the customer's trust in the vendor. On the technology side, trust is built through a belief that safety mechanisms are built into the website and by having a "*typical*" interface that is easy to use. On the customer side of the equation, trust is built through beliefs that the vendor has nothing to gain by cheating, that the interaction is "*normal*", and that the customer's institution-based trust (in the vendor) holds true. They asserted that "*institution-based beliefs of structural assurances and situational normality have by far the most effect on trust*" (Gefen et al., 2003, p. 72). McKnight et al. (2002a) make much the same claim and note that "*trust, as a willingness to depend on a vendor to deliver on commitments, is not the same as trust as a belief that the vendor uses consumer data ethically, or the same as trust as a perception that the Internet is technologically secure"* (D. Harrison McKnight et al., 2002a, p. 335). An emerging theme in our review of the study of trust in technological environments is that one must be quite precise in defining the dependent variable "*trust*".

Siau and Shen (2003) studied a narrower concept of mobile commerce but failed to explicate how the mobile environment influenced other e-commerce-based trust studies. Their work echoes much of the e-commerce work. Specific ways for companies to initiate customer trust in the mobile environment include familiarity obtained through frequent exposure, company reputation, quality of information delivered to customers (accuracy, timeliness, usefulness), third-party certifications, and rewards.

Awad and Ragowsky (2008) examined the influence of e-commerce "*word of mouth*" (WOM) on trust. Online WOM was an antecedent to trust in their work. Notably, men consider the ability to post information to be a positive influence on WOM quality. For men, the presence of an online WOM system on a retailer site contributes more to perceived trust of an online vendor than for women. Women discount the value of posting information but place greater emphasis on the responsiveness of other consumers to their contributions. Women value perceived ease of use (PEOU) more than men in establishing trust online. Online trust was found to be positively associated with intention to shop for both men and women.

3.3.5 Other Online Trust Contexts

Outside of e-commerce, McKnight et al. (2002a) studied trust in the context of an advice-giving website. In this case, their expected links between institution-based trust and trusting beliefs were not found. They conclude that while institution-based trust may be important in e-commerce websites, "*the relevant institutional context may need to be defined in more specific terms…, particularly as the Internet begins to be utilized for more specialized applications*" (D. Harrison McKnight et al., 2002a, p. 351). This conclusion supports Ridings et al. (2002) who cite Lewis and Weigert (1985b) and Luhmann (1979) in stating trust is dependent on the situation in which it is being considered. In their study of advisory information exchange, Ridings et al. (2002) found that trust influenced both giving and receiving advice between strangers in a virtual community, but the three distinct factors they identified were ability, benevolence, and integrity.

Looking specifically at online customer service, Turel et al. (2008) found trust in the online service was built through interactions with the customer service representatives. The development of this trust between the customer and the customer service representatives influenced the customer's trust in a firm's customer service operation.

Zahedi and Song (2008) studied the evolution of trust over time in an experimental setting of an online health infomediary. The results show that the structure of trust changes over time and information quality becomes the single most important antecedent in infomediary trust building. Satisfaction also plays an important role in changing Web customers' beliefs. They conclude that information quality is the "*single irrevocable and visible investment*" (Zahedi & Song, 2008, p. 243) that health infomediaries can make to influence consumers' trusting beliefs.

Trust has also been studied in the context of virtual teams, but technology was rarely a factor. Trust in virtual teams impacts performance (Kanawattanachai & Yoo, 2002), but the development of trust (initial and on-going) has been found to be influenced more by knowledge of the other team members (e.g., their backgrounds, professional credentials, and affiliations (Meyerson et al., 1996)) than by technological issues.

Notably, digital currencies and digital assistants have received little attention in the IS research literature on trust. Bitcoin was introduced in the 2008-2009 period as a reaction to a breach of trust in central banks when the recession occurred that year (Baldwin, 2018). Since then, many digital currencies have been introduced, such as Ripple in 2012, Ethereum in 2015, Zcash in 2016, and Cardano in 2017. Zcash is especially notable for *"the ceremony"* that was performed to create consumer trust in the currency (Peck, 2016; Webster, 2021; Zcash, 2021). As of 2019, there were over 2100 cryptocurrencies in the marketplace (Rehman et al., 2020).

Currency has three primary purposes: a medium of exchange, a unit of account, and a store of value. Digital currencies have been able to serve as a unit of account. However, the volatility of digital currencies has negatively impacted their ability to serve as a store of value. While succeeding as an investment instrument, digital currencies have had little success as a medium for exchange. They are only just beginning to be integrated into marketplace transactions. Trust in digital currencies has been closely tied to the underlying blockchain technology upon which they are implemented (Marella et al., 2020). However, blockchain technology alone does not generate trust. Rather, trust is derived from the systems and applications in which the blockchain technology is used (Shin & Bianco, 2020). With respect to cryptocurrency, Shin and Blanco (2020) conclude users' trust seems to be based on their prior experience and perceptions about other similar services. Rehman et al. reviewed blockchain trust research and state *"the term **trust** [their emphasis] has never been formalized or quantified"* (Rehman et al., 2020, p. 1201). In their review of blockchain research, the vast majority of which was drawn from engineering and technical online sources, they conclude that *"none of the studies focused on interweaved technical and nontechnical trust issues that are present in the cryptocurrency ecosystem"* (Rehman et al., 2020, p. 1197).

Similarly, how or why trust exists in digital assistants such as Siri (introduced in 2011), Alexa (introduced in 2014), or Google Assistant (introduced in 2016) has received little attention. For example, as recently as 2019 trust is not identified as an important AI-based digital assistant research perspective in a review of research opportunities (Maedche et al., 2019). As with digital currencies and blockchain, most of the studies of digital assistants (also known as AI-based assistants, smart personal assistants, voice-activated assistants, and voice-assistant systems) that have occurred are in more technical areas. Zierau et al. (2020) conducted a systematic literature review on the topic of smart personal assistants that is representative of this situation. Their study eventually reviewed 32 papers from a range of technical outlets, which included information systems journals (only 8 papers were drawn from the Association for Information Systems electronic library). Their suggested model for research has three perspectives: user interface-driven trust, interaction-driven trust, and explanation-driven trust. Lee et al. (2021) also focus on interaction quality as a critical factor influencing trust, and both interaction quality and trust as critical in the adoption of voice-assistant systems.

3.4 Discussion of the Issue

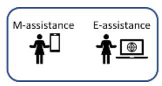
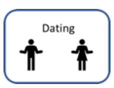
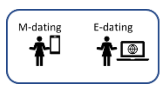
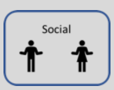
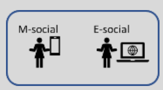
When we compare the technology-oriented trust studies from the prior section to the list of interpersonal factors, we can see potential opportunities to extend prior work in relevant directions. The conditions for technological trust in the context of interpersonal trust, professional trust, organizational trust, and finally for trust in long-term relationships are discussed.

Interpersonal trust conditions are described in Table 2. Similar to non-technology situations involving interpersonal trust, initial trust is important for personal trust in technology. As described in the table, trust in mobile or electronic (M/E) assistance technologies is built based on cues provided by the institution or based on experience in previous situations. The major gig companies create a network of trust for the user through numerous products. These build trust based on experience in previous situations. The experience and trust in the often-far-reaching product portfolio also transfers a certain level of trust in an assistance app included in the portfolio, e.g. a navigation app, even if it has never been used. Today, users receive more personalized recommendations through assistance systems, moving the experience closer to interpersonal face-to-face interaction. Strong linkages, such as a unified collaborative design, should support this transfer of trust within the product portfolio.

Another route to trust is taken by digital distribution platforms such as Apple's App Store. These advertise being a safe place for apps that meet strict privacy, security, and content standards, which is the electronic substitute for acquaintances and functions as a trusted third party. Additionally, users rate the experience, conveying a sense of trust, while metrics such as ranking, ratings, age, or adoption rate are collected. Through this trust, users become dependent on the dominant vendors through their trust systems. Consequently, any research involving a user's trust in, for example, Apple's Map app needs to also consider the user's perception of trust in any other Apple apps, the user's trust in the Apple Store, and the user's trust in Apple hardware. However, this creates a further complexity of trust for the user, namely with whom he has the trust problem. For the user, clear responsibilities are mixed up; take the XaaS concepts, for example, where one service provider makes solutions from another manufacturer available.

The second part of Table 2 examines technology development of M/E trust. Trust may not exist between all the parties using the technology. Users may trust the technology, but not the stranger with whom they interact through the technology due to a lack of indicators through which initial trust can be established. In the first two trust conditions in the table, the stranger has been replaced by the technology; in three and four, the stranger remains as part of the context of the situation. Research into trust in condition one can focus solely on the technology; there is no interpersonal trust to consider. In condition two, there should be a mix of interpersonal, institutional, and technology constructs to consider. A potential research question could examine the degree to which interpersonal, institutional, and technology trust are considered. Any study of trust in condition three and four must include interpersonal trust constructs as well as technology trust constructs, but condition four must also consider the complete range of trust issues described above regarding the use of an app. Such a study becomes even more complicated when the participants eventually meet face-to-face, as now the study should consider any factors regarding the meeting place and scenario plus any factors from each person's history that could be relevant. However, in these cases, one might be able to study the full range of trust development. Initial trust is involved in using this technology and in contacting another participant. Initial interpersonal trust can be destroyed when personal characteristics are misrepresented in user profiles. People believe they have met someone online and develop an apparent trust, which is shattered on a first date. Not only can the behavior be attributed to incorrect profiles, but often people behave differently online than offline, or traits are perceived differently. From a technology perspective, the quality of the interaction of the user with the technology could impact the development of trust between the people. Subsequent app use in these cases by a user who has experienced a breach of trust like this must be considered and separated from the technology trust aspects of the situation. Failure to do so will likely result in interpersonal trust issues confounding the results of a technology-based trust study or technology trust issues confounding the results of a study of interpersonal trust.

Table 2: Personal Trust Conditions: Interpersonal and Technology-based

#	Interpersonal		Technology	
1		Assistance: 1) asking a stranger for directions, 2) asking an acquaintance for directions.		M/E-Assistance: 1) checking a map app for directions.
2		Commerce: 1) with a stranger, 2) with an acquaintance (excludes professional retail).		M/E-Commerce: 1) through a gig-economy app like eBay or Amazon; 2) through a mobile / web commerce channel for a "brick & mortar" retail operation.
3		Dating: 1) asking a stranger for a date, 2) asking an acquaintance for a date.		M/E-Dating: 1) arranging to meet a stranger on a date.
4		Social: 1) interacting socially with a stranger, 2) interacting socially with an acquaintance.		M/E-Social: 1) through an app like Facebook or Twitter with an open profile; 2) through an app like Facebook or Twitter with a closed profile.

Professional trust conditions, ranked by the urgency of data / information exchange, are described in Table 3. Both the technical characteristics of the website and the customer's trust in the professional provider are the perspectives to be examined in this context. Similar to what was described previously, users trust the technology, but perhaps not the professional stranger interacted with through the technology. Again, there is a lack of indicators through which initial trust in their capabilities can be established. However, there is also a risk of misinformation in professional relationships. As with personal trust, professional trust also seeks to build initial trust through trusted third-party systems, such as certifications, recommendations, performance metrics, or user ratings. This is already being implemented in practice and has been scientifically studied by Ba et al. (2003), for example.

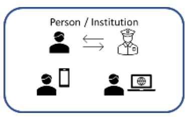
The benefit of a brand for building initial trust has been described several times in the literature. However, the transfer of trust from a non-technology-based brand to a technology driven brand has not yet been studied. A possible research question would be whether personally developed professional trust can be transferred to technology and whether it can be further developed there in the same way and later transferred back.

Another aspect is the potentially global communication environment that can be accessed by customers and professional providers. For example, a customer can access a global range of professional programmers, artists, or consultants. While interpersonal trust is usually based on local and thus regional offerings, professional trust can and does utilize the full potential of global communication. However, global communication should always consider local circumstances such as culture, tradition and code, regulations and laws. The practical answer at present is to rely on local trust systems, such as the evaluation of a customer from the region. However, how global trust can be transferred locally has not yet been investigated.

Condition 6 is characterized primarily by a high level of judgment and social and moral standards that are expected of a professional in addition to the actual competence. The challenge for the professional is that only the technical capabilities available (at the client and professional), such as video and audio, can be used to demonstrate the skills. Providers of medical online consultations, for example, primarily advertise initial care where further action is discussed. This raises questions about the long-term trust relationship: whether and to what extent the professional trust gained online can be transferred to offline, what technical possibilities there are for developing trust beyond the initial consultation, and how professionals can trust each other, e.g., in the event of a treatment transition (online - offline OR online - online). Research in this area must also consider the deference that people show when seeking advice from professionals. People not only trust financial, legal, and medical advisors / professionals to give good counsel, they defer to the experts due to their higher level of competence in an area. While McKnight et al. (2002a) considered *"general others' competence"*, it is unclear that they explicitly considered this how this deference impacted their results. How this human nature influences the trust relationship in an online setting must be a factor in such a study.

The 7th condition extends prior social and organizational trust through the structural assurances and situational normality. Institutional trust is extremely sensitive, and an erosion of trust in shared institutions leads to a loss of trust in other people. In the context of institutional trust, observations can be made about professional and technical trust. Interpersonal trust relationships between users and professionals of institutions are not desired, and professional trust is projected onto the institution rather than individuals, thus not realizing its full potential. Technical trust is severely limited because the level of digitization in institutions is low and institutions rely on offline means to avoid misinformation, such as ID cards or mail service to verify users. Research is needed to determine how the sensitive trust of the institutions can be further transferred to technology and how long-term professional and personal trust development can be established.

Table 3: Professional Trust Conditions: Interpersonal and Technology-based

5		Commerce through established retail corporations; social networking sites; professional networking sites; assistance where competence disadvantage may be critical but not life-threatening (e.g., diy repairs).
6		Assistance or commerce through established corporations / organizations where competence disadvantage exists and may be impactful on life (e.g., medical, financial), excluding government institutions.
7		Assistance or commerce through established government / nongovernment institutions (e.g., police, government agencies, religious organizations).

Organizational trust conditions are shown in Table 4. Organizational trust permeates interorganizational and interpersonal trust and cannot be viewed in isolation. The advantage of business relationships is that initial trust is supported by organizational affiliation, so there is an element of trust.

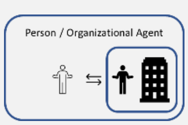
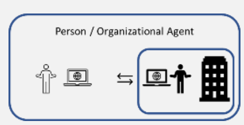
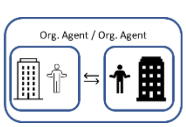
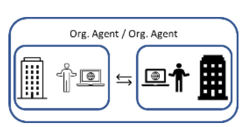
Condition 8 assumes that we trust the employees of a renowned company equally because of its online presence. The corporate brand manages to transfer the trust it has built up to its employees online as well. In practice, many companies have already taken this step. However, two points remain unnoticed. Similar to what was described earlier, technology does not cover all sensory perceptions compared to physical presence. A question to study is: How can the in-person cues used to develop trust be bridged by technology? Second, there is a difficulty for startups or regionally limited brands: How can a new/unknown brand build and activate new or regionally limited trust in a global context?

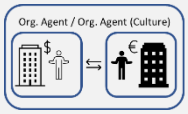
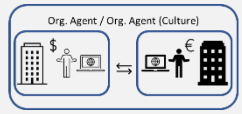
The 9th context describes interorganizational trust, i.e., the trust placed in a partner organization. In the interaction between organizations, organizational culture, habits and processes are added as complex levels. Third-party certified digital badges, for example, attempt to create an overarching standard in education and training that can be trusted. And where independent action and responsibility can be taken in personal relationships, defined rules and processes must be taken into account in organizations. In virtual project teams, for example, different competencies come together. How bridges and thus trust can be created between them remains undescribed. Similarly, the economic effects of trust, such as Williamson's (1993) transaction cost theory, must be considered for how they are activated in practice.

Condition 10 describes another complexity that has received little attention so far: the different cultures between companies, but also within companies. Metrics such as time, currencies, or simply things like different standards (e.g., paper size) make interaction difficult. In addition, different cultures require different levels of rules and trust. While a uniform standard is desirable, it is not feasible in practice. What are the economic consequences of the lack of trust due to cultural differences?

In conditions 8, 9, and 10, a reasonable question to examine is the extent to which interpersonal and institutional trust must develop or exist prior to the establishment of organizational trust. Can organizational trust really exist in the absence of some interpersonal or institutional trust existing somewhere in the social / technical system? What are the relative amounts of interpersonal, institutional, and organizational trust that compose a trusting relationship at the organizational level? In these cases, is technology a direct effect or a mediating or moderating effect on the development and maintenance of trust?

Table 4: Organizational Trust Conditions: Interpersonal and Technology-based

#	Interpersonal		Technology	
8		Interaction as an individual with a person acting as an agent of an organization. This could range across all of the situations (professional norm, professional competency, institution).		Interaction through a technology interface (e.g., email, chat, video) as an individual with a person acting as an agent of an organization. This could range across all of the situations (professional norm, professional competency, institution).
9		Interaction as an agent of an organization with a person acting as an agent of an organization. This could range across all of the situations (professional norm, professional competency, institution).		Interaction through a technology interface (e.g., email, chat, video) as an agent of an organization with a person acting as an agent of an organization. This could range across all of the situations (professional norm, professional competency, institution).

10		Interaction as an agent of an organization with a person acting as an agent of an organization embedded in a different culture. This could range across all of the situations (professional norm, professional competency, institution).		Interaction through a technology interface (e.g., email, chat, video) as an agent of an organization with a person acting as an agent of an organization embedded in a different culture. This could range across all of the situations (professional norm, professional competency, institution).

Other trust conditions that need to be studies include the growing use of blockchain technology, digital currencies, and AI-based digital assistants. People trust social media more than blockchain because they are more familiar with it (Shin & Bianco, 2020). However, the underlying technology of blockchain is likely much more complicated than most users perceive any social media technology to be. As with other technologies, trust research must distinguish between trust in the blockchain technology (i.e., the architecture, programming, and processes) and trust in the applications built on blockchain technology (Zavolokina et al., 2020). However, research that focuses on trust in a blockchain application must follow the same guidelines as described above for any other application. Specifically, the portfolio of applications developed by the same vendor, the blockchain technology, and the hardware used must all be considered in assessing the level of trust in the application. Another question that could be studied is: Is trust in blockchain dependent on understanding the underlying technology?

Intention to use digital currencies can be studied using technology acceptance models (see Almuraqab, 2020). However, digital currencies research must also consider the blockchain technology that digital currencies are based on, the institution behind the digital currency (in many cases today, a start-up enterprise), and any other applications distributed by the same organization backing the digital currency. Other factors that must be considered are the lack of a centralized banking institution to support the currency, the volatility of the currency, how it fares with respect to the common uses of money, the inability to transfer the wealth one has in digital currency to an heir or other agent, and the lack of insurance available for wealth held in this form. A paradox of digital currency implementations is that the open systems that exist for transparency which is intended to build trust also make the system vulnerable to malicious actors. In the case of centralized institutions offering digital currencies, those institutions must still cultivate trust in the digital offering (Söilen & Benhayoun, 2021). Even the political / governmental environment in which the digital currency holder lives must be considered, since digital currencies are being collected by some people exactly because they have little or no trust in their country's financial institution stability.

Research on trust that involves AI-based digital assistants promises to be a very complicated and complex endeavor. Depending on the situation, every trust factor described in this review could be relevant. Additionally, the anthropomorphic aspects of the voice-activated assistants such as Siri and Alexa will require including some examination of the trust a user has that is dependent on the characteristics of the AI-based agent. For example, does the voice respond in a way that build trust? When an AI-based assistant provides inaccurate responses, does it make sense to speak of "forgiving" the device?

Long-term trust conditions have not yet been capitalized on in technology; so far, most of the focus has been on initial trust, rather than the associated impact of long-term development. What can technology do to encourage, reward, and cultivate conditions necessary for a gradual development of trust? As described in Lewicki and Bunker's (1996) transitional stages of trust, as activities are validated in terms of trust, parties begin to build a knowledge base about their needs, preferences, and priorities. The transaction cost theory of Williamson (1993) follows thereby a similar thought. According to it a transaction can be settled and organized more or less efficiently. In a perfect market the transaction costs go to zero. There social control mechanisms are already significant such as trust, culture, and reputation for the transaction costs. An adaptation of this transaction concept for trust in the context of technology could map personal, professional, and organizational trust interactions in a trust stage model, and promote benevolent behavior through lower (transaction) costs. For example, a user in a higher trust stage receives an offered item more favorably because the expected transaction costs are lower. Perhaps such a concept could be adapted in trust technology, and one could be created that develops and promotes personal, non-transactional trust exchange, such as dating or social contact.

One way to provide information to users to build trust over the long-term is to develop technology maturity models enabled by business models that include trust as a maturity dimension. As a logical consequence and next step, we therefore see two steps: 1) The development of a business model that promotes long-term trust by lowering transaction costs between the actors and 2) A maturity model that promotes long-term trust in the digital transformation of resources. By combining a business model and a maturity model, both of which promote long-term trust, the goal is to ensure that after the initial trust, there is an interest among the actors to build a long-term trusting relationship.

3.5 Conclusion

This study has provided a rigorous overview of the current theory of trust in the interpersonal domain and trust involving technology within information systems. It also shows that trust is a very complex topic and that technology-based trust will and must continue to be developed further, both in practice and in theory. What is needed now is a balance between acquired and practical relevance.

The theoretical understanding of trust has shown that trust is diverse. There are various combinations of relationships between individuals and organizations where trust should be placed above one's own immediate interests or expected benefits, but this does not exclude the possibility of deception. Trust includes both personal and institutional trust, which is bounded by security & policies but already includes influencing factors such as personal characteristics. The types of trust examined are articulated, authentic, basic, blind, calculation-based, characteristic-based, deterrence-based, dyadic, identification-based, impersonal, knowledge-based, simple, interpersonal, interorganizational, and institutional. Initial trust is the most challenging and has been the subject of much research. The development of long-term trust, on the other hand, goes a step further and examines how trust can be built over the long-term and how parties behave to further strengthen it. Currently in technology research, the development of long-term trust has not been studied extensively.

The most significant trust paradox relates to initial trust and is the biggest challenge to trust in technology. The literature indicates that trust can only be built if a certain level of trust can be assumed, but trust cannot be assumed if there is no basis for trust. Trust in technology within information systems has been researched for over two and a half decades, but the rapid pace of advances in technology call into question whether studies from twenty-plus years ago are still relevant. Even studies that are only fifteen years old predate technological advances such as digital currencies, most social media in use today, and AI-based digital assistants. Research on (reasonable) trust in the technology itself and in designers, trust-related characteristics of online interaction, initial trust (cues) in online environments, cultural differences, trust and satisfaction, technological trust factors such as trusted third parties or seals of approval, and e-commerce trust such as commitment compliance are all studies that warrant re-examination.

One of the key findings in the research that has occurred is that trust in many online environments has little to do with the technology itself. People trust people, not technology. Technological artifacts are not ascribed awareness or agency, so trust is placed in the designers of the technology. But is this true today for the generation of people who have only known an interconnected, digitally networked world? Will it continue to be true as technologies become more complicated (e.g., blockchain) and more human-like (e.g., Siri and Alexa)?

In the discussion it could be shown that the research field of technology-based trust and the practical implementations in information systems have not yet reached the depth that interpersonal trust theory has. It was organized into four sub-areas, namely interpersonal trust, professional trust, organizational trust, and finally trust in long-term relationships.

In the *personal relationship* of the interpersonal trust, there is still a need for research on how technology can promote the establishment of initial trust with a stranger, such as in dating or social interactions. In the case of assistance systems, the extent to which interpersonal trust is taken into account versus the extent to which trust in technology is taken into account should be investigated. We've also seen the complexity of trust increased by technology, as in cases of XaaS, where it becomes more difficult to know with whom one may have a potential trust issue. In the area of commerce and dating, the entire range of interpersonal as well as technological trust development should be examined.

In the area of *professional trust*, the question is whether and to what extent professional trust can be transferred online and vice versa. Another candidate for study is how globally acquired professional trust can be transferred locally. There are three gaps in trust based on different competencies: first, whether and to what extent professional trust acquired online can be transferred offline; second, what technical possibilities exist for developing trust beyond the initial consultation; and third, how professionals can trust each other. The biggest gap, however, is in institutional trust and the question of how sensitive trust can be transferred from institutions to technology and how long-term professional and personal trust development can be established.

Organizational trust has already been extensively studied, but there are still gaps here as well. How can technology be further activated in the area of interaction with companies to enable more sensory perceptions for building trust between customers and companies? And how can a new or as yet unknown brand build and activate new or regional trust in a global context? In the area of trust between organizations, the question is how to build trust in virtual teams without testing each other's competencies. More generally, how can economic benefits generated by trust between organizations be activated and exploited in practice? And finally, how big are the economic consequences of a lack of trust due to cultural differences?

We have found that initial trust is already being used in various contexts, but that the *long-term development of trust* and its effects are not yet taken into account. The long-term trust relationship is a basic prerequisite for the existence and development of many platform business models. Platforms play an important role because they can reduce transaction costs between participants and because they are powerful digital business models that are adaptable and able to manage complexity, scale quickly, and create value (Abdelkafi et al., 2019). In this area, what can technology do to encourage, reward, and cultivate the development of conditions necessary for trust? Therefore, first, a business model is needed that promotes long-term trust by lowering transaction costs between actors. Second, a maturity model that promotes long-term trust in the digital transformation of resources. This combination of long-term trust promotion should ensure that after the initial trust there is also an interest in developing it further in the long-term.

3.6 Acknowledgements

This work has been funded by the Federal Ministry of Education and Research (BMBF), Germany under the funding code 16DHB2112. The responsibility for the content of this publication lies with the authors.

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Chapter 4

4 Paper 3: Digital Laboratory Transformation Maturity Model

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Abstract: This paper presents a maturity model for digital lab transformation effectiveness. The model fulfills three practical goals: 1) to establish comparability of the effectiveness of the digital transformation of labs, 2) to provide lab operators with a guide for (further) transformation, and 3) to build initial trust among lab users. In addition, the maturity model contributes to the literature on digital lab transformation by capturing, describing, structuring, and evaluating relevant dimensions, items, and levels. To this end, the design science of information systems methodology was applied and the associated six process steps were followed. The resulting maturity model artifact for effectiveness of digital lab transformation is based on a structured literature review and was evaluated through an expert workshop and expert interviews based on 11 case studies. Confirmed potential objectives of the maturity model, strengths and weaknesses, areas for improvement, and practical and reusable recommendations emerged from the interaction with the experts. Finally, based on the expert capabilities, the added value of the maturity model for online lab types and functionalities, the international applicability of the online lab, and finally the sustainability of the online labs is highlighted. Especially for use cases in manufacturing technology, the authors see application potentials for the use of online labs from an organizational point of view, but also from the point of view of the stakeholder, such as users and operators with manufacturing background, who use and develop transformed labs.

Keywords: Digital transformation, Laboratory effectiveness, Online laboratory, Maturity model, Sharing economy

4.1 Introduction

Education has changed significantly in recent years, not least because of changes in pandemic demands. Distance learning, where teachers and learners are physically separated, is becoming increasingly important and continues to drive the digital transformation in the classroom. On the other hand, STEM subjects such as engineering education, which teaches the handling of materials, energy, and information (Feisel & Rosa, 2013), or manufacturing education, which teaches industrial design and the production of finished products, require hands-on and experimental training, so hybrid models are necessary. Successful teaching can only be achieved through a combination of approaches that combine theoretical courses with practical work, such as laboratory (lab) work (Kara et al., 2010). Labs provide students with a special hands-on engineering experience and allow them to explore systems and their real-world behavior (Zutin et al., 2010). In the lean manufacturing lab, for example, students learn value stream management using a manual assembly line through the operation of a production line, as well as buffer, waste and congestion management (Oberhausen & Plapper, 2015). For learning purpose, several basic lab criteria for engineering program accreditation (ABET) and lab objectives such as those of Feisel and Rosa (2013) or the KIPPAS categories of intended learning outcomes for lab learning (Brinson, 2015) have been established (Ma & Nickerson, 2006; Morales-Menendez et al., 2019). However, real labs have disadvantages for the user, such as the student, and the lab operator, such as the universities or industry. The disadvantages for the user include fluctuating quality of lab instruction, crowded labs, restriction of independent work, limited time for experiments, or inadequate safety measures (Achuthan & Murali, 2015). The operator struggles with a lack of adequate work space, expensive and inadequate lab infrastructure, intensive and expensive maintenance of equipment, regular updating of experiments, rising costs of supplies and consumables, fluctuating workload, funding cuts, frequent career changes of staff, and a lack of competent technical staff (Achuthan & Murali, 2015; Chowdhury et al., 2019; Frank & Kapila, 2017; Macías et al., 2007). In addition, there is a large discrepancy between lab facilities in rich and developing countries (Achuthan & Murali, 2015).

An efficient and economically feasible solution to the drawbacks of real labs that also addresses distance learning is the use of information and communication technologies (ICT) to provide lab experiences (Mani & Patvardhan, 2006). Online labs are ICT-enabled experiments that can be accessed via the Internet to gain hands-on experience and to become familiar with real-world phenomena (Zutin et al., 2010). According to Zutin et al. (2010), online labs are divided into software simulations (or virtual labs) and labs consisting of real hardware equipment (or remote labs). A more extensive examination of the different lab classifications can be found in (Esposito et al., 2020), where the authors distinguish between a) real or virtual lab, b) local or remote location of the experimenter, and c) on-site or Internet access. However, the advantages of online labs over real labs are characterized by 1) availability: users can use online labs from anywhere and at any time, 2) observability: observed or recorded for single and multiple users, 3) accessibility: usable by people with disabilities, and 4) safety: alternative to dangerous experiments (Heradio, La Torre, Galan, et al., 2016). The expanded availability of online labs provides the operator with far-reaching opportunities to increase the degree of use of the labs, as they can also be used during non-instructional times (Gardel et al., 2012), and to scale the labs by making copies of the experiment (Harward et al. 2008).

By making the labs available online, they can be shared with other facilities and users. The so-called sharing economy describes a behavior that promotes the shared use of resources, thus benefiting from higher resource utilization, cost advantages and access to new knowledge (Goudin, 2016). This makes online lab candidates for the use of shared knowledge, shared infrastructure, and shared facilities through the application of ICT technology. This approach of online lab sharing has already been discussed by Seiler (2012) on lab as a service, by Uckelmann (2012) for sharing logistic labs, by Gode and Madankar (2013) on promoting lab sharing, by Heradio et al. (2016) on cross-institutional lab sharing, by Orduna et al. (2016) on lab sharing economy platforms, and by (Kammerlohr et al., 2021) on business models for lab sharing. The biggest challenge in sharing is mutual trust (Gossen et al., 2019), which is also evident from the previously mentioned publications. The user must trust that the lab will be available at the right time in the expected condition, whereas the operator trusts that the lab will be used correctly and under the agreed conditions and that no damage will occur. In the case of online goods such as online labs, the parties involved may not know each other and must be able to trust that each other's requirements will be met. Independent third-party agents provide cues for this, helping to build initial trust before one's own experience can be gained (Ba et al., 2003). For online labs, a maturity model could be a kind of indication of a third party that describes how effective the lab's digital transformation is. If a lab has a high maturity level, a user should be more confident that the lab meets the requirements of digital transformation.

Pousttchi et al. (2019) describe digital transformation as the *"direct and indirect effects of the application of digital technologies and techniques on organizational and economic conditions on the one hand and new products and services on the other "*. Various maturity models exist that describe the maturity of digital transformations. Deloitte's Digital Maturity Model, for example, describes five business dimensions that are intended to describe the maturity level of an entire company in the communications industry and is a tool for creating guidelines for the path through transformation (Deloitte LLP, 2018). The Industrie 4.0 Maturity Index, which is based on an acatech study, focuses in particular on new business models, the sustainable and efficient use of limited resources, and the cost-efficient production of highly customizable products in manufacturing (Schuh et al., 2017). Specifically, for lab transformation, various studies have been conducted to measure this change in the lab, making its effectiveness transparent to stakeholders. However, these are currently limited to didactics and technology and do not cover the organizational aspect. The pedagogical effectiveness of the transformation of online labs as an indicator of the usefulness of an experiment in achieving the desired goal has been studied by several authors (Achuthan & Murali, 2015; Brinson, 2015; Gadzhanov & Nafalski, 2010; Heradio, La Torre, & Dormido, 2016; Mani & Patvardhan, 2006). In addition, the technological transformation of online lab, for example, to design, develop and implement various digital labs, has been studied by several authors (Azad, 2020; Besic et al., 2019; Kim et al., 2019; Prada et al., 2015). For both areas, corresponding maturity models can also be found in the literature. For example, the Learning Labs Maturity Model is designed to help educators and organizations assess learning lab requirements and decide which learning lab features to use at each stage (Abbas, 2019). In contrast, the Chemical Security Assessment Model is designed to help chemical facilities and labs determine the maturity of the chemical security program (Skare, 2021).

It can be summarized that real labs are necessary units in technical education, but they have far-reaching disadvantages for operators and users. Online labs that demonstrate digital transformation have evolved to offer a solution to this problem. Research by Uckelmann (2012) has shown that in addition to didactics and technology, an organizational element is required for digital transformation and sharing of online labs. There are technical and didactic models to measure the effectiveness of digital lab transformation, but a model that takes into account the organizational shift to sharing between institutions and thus the needs of users and operators is currently missing. The organizational effectiveness of digital lab transformation has not been further explored since, but is gaining importance due to changing lab sharing requirements such as building initial trust between different actors and organizations over time. Numerous international online lab research projects have failed to continue the developed environments after the project funding phase (Esposito et al., 2021), not least because of the lack of effectiveness. However, the number of initiatives for online labs remains high, but according to Orduna et. al

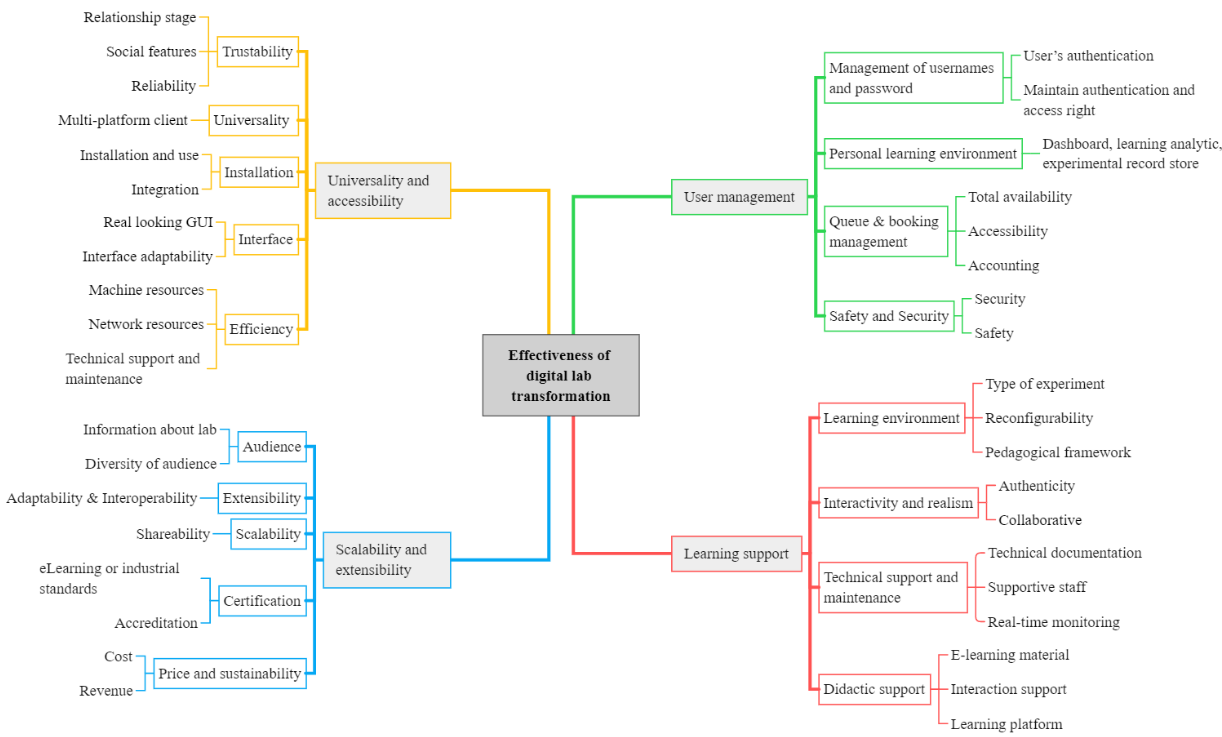
(2016), there is a lack of initiatives to share them beyond their own institution. We define digital transformation effectiveness as the integration of digital technology that leads to fundamental desired or intended changes in the way labs operate and how they deliver value to their customers. Therefore, the research question explored is, **(RQ)**: Can the effectiveness of digital lab transformation be adequately described in a maturity model and thus used as a tool to support the sharing economy? Both qualitative and quantitative goals are addressed by a solution to the problem. Qualitatively, a model describing the effectiveness of digital lab transformation, with evaluated dimensions, items and levels, and quantitatively, as an indicator in the design, implementation, or expansion of digital lab transformation of how and where the desirable solution would be better than the current one. The practical benefits promise comparability of the effectiveness of shared labs, both from the operator's perspective in terms of administrability, financial and personnel effort, and from the user's perspective in terms of learning success. A systems view of organizational effectiveness can provide (1) a context for understanding previous studies, (2) a guide for designing new studies that lead to a better understanding of operational and business model transformation, and (3) an artifact for users and operators for transforming the lab to enable the sharing economy.

The rest of the article is structured as follows. First, we present the theoretical background on effectiveness of digital lab transformation. Second, we describe and justify our methodological choices. Third, we report the results of the expert workshop to develop the maturity model concept, and fourth, we report the results of the expert interviews on the refinement of the maturity model using case studies. We then discuss our contributions to literature and to practice, as well as limitations, and finally we summarize the practical application of the maturity model and future research directions.

4.2 Theoretical Background on Effectiveness of Digital Lab Transformation

The current literature on online labs provides a conceptual foundation for studying the phenomenon, but it does not explain how the effectiveness of the digital lab transformation forms. A search on Scopus served as the basis for the literature review (LR). Title, abstract, and keywords were searched for different lab types and effectiveness ("remote lab*", OR "virtual lab*", OR "online lab*", OR "real lab*", OR "digital lab*", OR "hands-on lab*", effectiveness) over the period 2000 – 2021 (as of June 2021), followed by a keyword filter ("Cost Effectiveness" (#74), "Automation" (#22), "Laboratory Equipments" (#20), and "Costs" (#17)). This resulted in a selection of 121 publications, some of which, as described earlier, were not relevant because they related to technology and didactics, e.g., the didactic effectiveness of two lab scenarios or the effectiveness of a simulation of a technical solution. With the help of the abstracts, the non-relevant papers were further sorted out and only those related to effectiveness of digital lab transformation were focused on, resulting in a selection of 45 publications for the following LR presentation. As a basis for the LR dimensional structure, we drew on the characteristics of Garcá-Zubía (2021), which originally described the requirements for a remote lab management system and the characteristics of a remote experiment. The dimensional structure of the effectiveness of the digital lab transformation can be seen in Figure 5, and consists of the dimensions of universality and accessibility, user management, scalability and extensibility, and learning support.

Figure 5: Theoretical Background Overview on Effectiveness of Digital Lab Transformation, Dimensional Structure According to Garcá-Zubía (2021)



4.2.1 Universality and Accessibility

The first of the four requirements is universality and accessibility. It describes whether and how a lab is accessible to the user in any technological scenario, referring to the original design of the experiment (García-Zubía, 2021). In this regard, Prada et al. (2015) add simpler support and efficient management. We distinguish in the following five subsections.

Trustability refers to the institutions and their capabilities that ensure the availability of the labs. Trust theory distinguishes between trust that is already established on the basis of an existing trust relationship and trust that must first be built. In addition to initial trust, there are trust models that reflect the development of trust during the interaction of the parties, such as that of Lewicki and Bunker (Lewicki & Bunker, 1996). Their transitional stages of trust development model describe how two parties form and develop a new relationship and explains how trust and relationships change, develop, or decline over time and how trust can be restored. In doing so, the transitional stages of trust model maps different benefits and different costs for each stage (sequential iteration) (Lewicki & Bunker, 1996). In practice, attempts are made to build a community through lab federation, which can create long-term trust. A lab federation pursues, on the one hand, the goal of federal load balancing by redirecting users to vacancies in other facilities and, on the other hand, transitivity through the possibility of sharing labs under existing contracts (Orduna, 2013). However, a federation requires sharing mechanisms to ensure the reliability of the host institution and its ability to fix problems when they occur (Orduna et al., 2016). A distinction is made between the type of participants in the federation, which can be individuals or any type of organization such as universities, institutions, or industrial companies (Zutin et al., 2010). A detailed analysis of trust-based requirements and the types of trust participants have when sharing labs was conducted by Baalsrud Hauge et al. (2019). Key requirements include the state of the lab, prior experience, constraints and compensation, behavioral congruence among actors, and regulatory issues and dispute resolution (Baalsrud Hauge et al., 2019). Orduna et. al (2016) suggests social features for this purpose, such as rating resources, adding comments, or tags. The importance of trust on the business model was also highlighted by (Kammerlohr et al., 2021), whereby trust stimulates the network effect in the platform economy to share labs. Another large part of trustability, besides social trust, relates to the reliability of the systems and hardware used (Orduna et al., 2016). At its core is the controllability and observability of the lab, which is characterized by the architecture and design, as well as the monitoring system. The architecture and design should be such that it supports the reliability of the lab as a whole (Hashemian & Pearson, 2009; Villar-Martinez et al., 2019). For example, multiple lab instances can operate in parallel so that operations can be maintained even if one instance fails (Villar-Martinez et al., 2019). As a solution, a real-time assessment and monitoring system supports lab reliability and traceability and quickly uncovers failures (Gruson, 2018; Hu et al., 2006; Kara et al., 2010). Depending on the setup, trust in the institution may be more or less significant, e.g., if the lab is reliable as a simulation and is always freely available (Orduna et al., 2016).

Universality describes platform independence and thus ease of access. The architecture should be accessible regardless of platform, device, or operating system (Villar-Martinez et al., 2019). Zutin et al. (2010) specifies universality by focusing on client needs. Broadly speaking, any type of device, whether computer, tablet, or smartphone, should be freely accessible, so this is not dependent on one technology (Border, 2007; García-Zubía, 2021). Furthermore, Prada et al. (2015) suggests open standards as a possible solution to achieve platform independence.

Installation considers both the installation itself and the integration with a third-party system. Without installing software, configurations, or plugins, access to the lab should be developed and implemented (Bencomo, 2004; García-Zubía, 2021; Villar-Martinez et al., 2019). Technical documentation of hardware and software (client technology, runtime engine, client OS, browser) and access requirement (open access, access on demand, restricted access) facilitate access (Zutin et al., 2010). The second issue is integration with heterogeneous learning management systems or learning platforms such as Moodle or Canvas (Azad, 2020; García-Zubía, 2021; Tawfik, Sancristobal, et al., 2014). Customers expect an access portal or repository for different labs (Kondabathini et al., 2011), with integrations of pedagogical tools, supporting apps, or repositories that connect them (Orduna et al., 2016). These support through pedagogical frameworks, collaboration tools, and reusability of content and tools (Orduna et al., 2016).

Interface to the experiment should replicate the working environment of the real lab (Corter et al., 2011; García-Zubía, 2021). First and foremost is the real-looking graphical user interface (GUI), which should give the user the feeling of working in the real lab (Machotka & Nedic, 2009). This includes user-friendliness, as the degree of ease with which the user can navigate the environment, and intuitiveness, which captures the degree to which the interface to the lab is engaging (Mani & Patvardhan, 2006). An area that is often neglected is also access and support for people with disabilities (Gode & Madankar, 2013). In principle, the GUI should aim to compensate for the absence of the tutor (Bencomo, 2004). Direct feedback from instruments and components to the user via a webcam or microphone (García-Zubía, 2021; Machotka & Nedic, 2009) and available information such as software, instructions, advice and help, data, images, or tools can be helpful (Kara et al., 2010). In addition to the visualization of the experiment, the results or data should also be retrievable and displayable in the interface (Bencomo, 2004; Ying & Zhu, 2004). Furthermore, the interface should be customizable to the user's needs (García-Zubía, 2021). Immediate and individualized or target group-specific access to all information for different pedagogical levels, difficulty levels, and computing environments is required (Kara et al., 2010).

Efficiency describes the factor of required resources, technical but also human. The goal is to minimize the use of resources without compromising the quality of the experiment (García-Zubía, 2021). Speed, system accessibility, and seamless integration are factors (Hashemian & Pearson, 2009; Prada et al., 2015), as is the required network bandwidth demand and consumption (García-Zubía, 2021). In addition, efficiency also describes the amount and duration of machine resources required (Elawady & Tolba, 2010). As an example, Elawady and Tolba (2010) and Gode and Madankar (2013) developed a lean design that uses few machine resources and low Internet connectivity, such as through a lean web server and a lean website interface. In addition to the technical resources required, the human one is elementary. What technical support and maintenance is required because science and engineering labs are difficult to maintain due to costly and complex equipment (Gode & Madankar, 2013)? Depending on this, vendor responsiveness is important. Considerations include whether multiple instances are operated and whether technical administrators are available to support the lab, answer technical questions, and to what extent (García-Zubía, 2021; Gode & Madankar, 2013; Zutin et al., 2010). Exception handlers that find, fix, or report anomalies are also used to save resources (Ying & Zhu, 2004). This expected high efficiency and resulting low staffing requirement directly competes with the didactic support described below, for which high staffing is desirable.

4.2.2 User Management

The second of the four requirements is user management. User management consists of four subsections that describe how the users get access to the online labs, how their data is managed, what user rights they have, and the storage of their experiment data set (García-Zubía, 2021; Ying & Zhu, 2004). Some of the solutions described here can also be maintained via a learning management system instead of in the online lab itself, but it is important that the following functions are covered (García-Zubía, 2021; Kara et al., 2010).

Management of usernames and password describes the controlled mechanism to provide legible and secure access to the online lab (Kondabathini et al., 2011). Typically, access to experimental equipment should be restricted to a specific group (Heradio, La Torre, & Dormido, 2016). User registration for authentication and authorization acts as a deterrent and can cause problems (Yeung et al., 2010). A single sign-on (SSO) functionality is recommended to simplify use and support interoperability (García-Zubía, 2021; Yeung et al., 2010); various authentication and authorization protocols such as Shibboleth support this. In addition, a rights allocation system based on the different user groups and institutions should be managed to achieve different levels of clearance depending on the lab setup (Li et al., 2009; Ying & Zhu, 2004). Besides user registration, subsequent management of authentication and access rights must also be maintained (Kara et al., 2010).

Personal learning environment describes the facilitation of an individualized and informal learning environment (Tawfik, Salzmann, et al., 2014). For pedagogical effectiveness, a personalized environment should be created to collect individualized data and conduct learning analysis to observe and know what benefits students are getting from online labs (García-Zubía, 2021). An experimental record store can also help to individually analyze the collected data using analysis tools (Ying & Zhu, 2004).

Queue & booking management or scheduling system describes the application that can be used to reserve lab resources for a limited time without conflict, thus preventing parallel use (Kondabathini et al., 2011). There are two options for this, either a queue where one waits until the lab is free or a booking system where a free time slot can be reserved (García-Zubía, 2021). Ideally, users should not have to wait for a free lab experiment, as this reduces overall availability and efficiency (García-Zubía, 2021). Several solutions for lab booking already exist, such as Moodle plug-ins (Gardel et al., 2012), although integrated solutions for accounting are still rare. An example of a booking process can be found in Gode and Madankar (2013), where registered users specify resources, times, durations, and intervals for labs in the booking menu. The booking process is influenced by the reason for use, e.g. whether the lab is being used for the first time, regularly, or by experienced users (Border, 2007; Lindsay et al., 2009). An important parameter is the total availability of the lab. This should not be subject to time constraints, except when an experimental environment is already occupied or maintenance is being performed (Bencomo, 2004). Availability of the lab should be designed for simultaneous accessibility for multiple users and is distinguished into synchronous mode, asynchronous mode and schedule mode (Elawady & Tolba, 2010; Ying & Zhu, 2004). These directly affect the operational latency: the waiting time before a student can access the experimental setup (Mani & Patvardhan, 2006). Another factor is the accessibility of the lab. This is referred to as freedom of access (Mani & Patvardhan, 2006) provided that access is independent of time and location and should be based on user needs (Kara et al., 2010). Shvets and Kukk (2011) calls this low-level time-sharing, referring to usage without pre-registration so that the user gets instant access. The booking of the lab leads to a billing, which is charged to the user. The basis for accounting arises from the booking system, but is influenced by the underlying business model (Kammerlohr et al., 2021). Orduna (2013) describes three basic accounting scenarios: Cost per access, fixed price per number of accesses, and fixed rate per time. The accounting system should offer enough flexibility to cover the bookings based on these scenarios.

Safety and Security must be ensured for the user and the operator as well as for the security of the system itself and its data. Uckelmann et al. (2021) has produced a guide for assessing safety and security in federated labs. System security is to prevent users from interfering with the server's functions, gaining access to private resources, or impersonating someone else (Ying & Zhu, 2004). The server software must isolate the system and network layers to prevent access outside the lab to protect against hostile or accidental actions that could damage or destroy the system (Bencomo, 2004; Hu et al., 2006). From a user's perspective, security should also not be compromised by the need to disable insecure ports or firewalls (García-Zubía, 2021; Gruson, 2018). Security policies with clear plans, rules, and practices are recommended, where users enter specific codes or passwords to log in (Hashemian & Pearson, 2009). This includes data encryption technologies such as SSL for secure data transmission (Orduna, 2013). For this purpose, Elawady and Tolba (2010) describe an encryption and decryption layer on both sides of the online lab. In addition, the operator must secure the lab and systems so that they are not damaged or destroyed (Ying & Zhu, 2004). Safety describes the operational safety of labs for personnel, equipment, and the environment (Achuthan & Murali, 2015). Online labs appear safer and less error-prone (Zhang et al., 2018), but even here, hazards should be avoided. To increase safety, a high level of automation (Bencomo, 2004) combined with real-time monitoring (Ying & Zhu, 2004) is a suitable approach. Experiment-specific monitoring solutions such as temperature sensors can additionally increase safety (Gruson, 2018). As a safety example, Achuthan and Murali (2015) describe possible toxic reagents or products that may have very undesirable effects, which should be considered. Further attention should be paid to the disposal of the (hazardous) substances used after the experiment (Achuthan & Murali, 2015).

4.2.3 Scalability and Extensibility

The third of the four requirements is scalability and extensibility, which consists of five subcategories. Scalability and extensibility describes how easy it is to adapt the labs to new target audiences, extend them with more experiments, scale them to more facilities, certify the results, and ensure sustainability (García-Zubía, 2021).

Audience describes the population served by the online lab; which demands, problems or needs the target group should have. First, this is determined by information about the lab, such as the type of lab, lab equipment, user groups, available language and cultural nuances (Yeung et al., 2010), or trial duration, which allows potentially interested parties to search for suitable labs (Zutin et al., 2010). Furthermore, information about the lab can provide information about the owner (person or organization such as university or company) (Zutin et al., 2010), or information about the type of experiment, such as batch experiments, interactive experiments, or sensor experiments, which further specifies the target audience (Harward et al., 2008). Second, about the diversity of the target audience, who is the user group, teachers, learners, or researchers (Sullivan, 2003). Which scientific or industry-specific field is being targeted, for example, electronics, mechatronics, or computer science (Azad, 2020; Zutin et al., 2010). Third, what level of education and difficulty is being addressed: primary, secondary, tertiary, research, or continuing education (Zutin et al., 2010).

Extensibility describes the ability of an online lab to be used beyond its original utility through adaptability, heterogeneity & interchangeability, and interoperability, which should enable a kind of plug-and-play paradigm (García-Zubía, 2021). Adaptability describes the capability of the lab architecture to easily connect components (Villar-Martinez et al., 2019), while still having a target-group-specific design (Kara et al., 2010). The idea is to create an adaptive learning system where users are able to customize and extend their courses according to their own preferences and needs (Mani & Patvardhan, 2006; Qu et al., 2019; Tawfik, Salzmann, et al., 2014). Heterogeneity and interchangeability describes interaction in a diverse system landscape through exchangeable modular online labs (Tawfik, Salzmann, et al., 2014). This involves the ability to handle different types of experiments (Azad, 2020) and the compatibility of experiments (Ying & Zhu, 2004). Interoperability describes the extent to which online labs can integrate or collaborate with other labs (Orduna, 2013). This includes modularity, described by Tawfik et al. (2014) as seamless and programmatic, which in turn emphasizes the flexible and reconfigurable design and adaptation of the structure of online labs (Azad, 2020; Elawady & Tolba, 2010; Frank & Kapila, 2017). An essential component is also the use of a standardized architecture, or rather open standards, and open source solutions, described, for example, in Zutin et al. (2010).

Scalability describes the ease with which copies of the system can be made in terms of the number of users as well as the number of experiments to serve a potentially unlimited number of users and online labs (García-Zubía, 2021; Harward et al., 2008; Orduna, 2013). Harward et al. (2008) outlines that access to the online lab may be limited only by equipment utilization or intentional restrictions imposed by the lab manager. Utilization fluctuations can be reduced by so-called lab federations that replicate labs in different facilities and provide shared access for them (Orduna et al., 2016). Lab manager constraints may include the number of courses, size of the work team, sharing of responsibilities, or support for concurrent users. As described earlier, large economies of scale and rapid expansion can be achieved through the sharing economy. Scaling through online lab sharing requires that labs be accessible both locally and remotely and have the necessary resources (Azad, 2020; Heradio, La Torre, Galan, et al., 2016). The initial requirements for a sharing platform that acts as a repository for online labs are described by Orduna et al. (2016) as requiring multiple providers, quality assurance mechanisms, simple contracts that require reliability and sustainability to increase lab sharing. Similar approaches are taken by Tawfik et al. (2014) with the use of a service broker or Yeung (2010) with so-called cataloging.

Certifications can help to increase scalability and extensibility. They validate, through third parties, on the one hand the learning content and on the other hand address the need of people who need a qualification certificate, for example for a professional change (Sullivan, 2003). An overview of different eLearning standards for online labs can be found in Tawfik et al. (2014) and Brinson (2015), which help to qualify learning outcomes. In addition, industry standards such as the 'ISO 9000 Family of Quality Management Systems Standards' can help to ensure that customer quality requirements are met (Bauer et al., 2015). Finally, accreditation plays a role, for example, to be integrated into a curriculum or to serve as performance indicators through badges.

Price and sustainability describes the ability of online labs to exist continuously and across product cycles, describing a fundamental need for scalability and extensibility. García-Zubía (2021) describes that the best way to ensure a high-quality service is to pay for it. Universities offer online labs for free, but this usually makes them unsustainable in the long run (García-Zubía, 2021). We distinguish into the two economic variables of costs and revenues. Costs describe the expenses of setting up, running, and maintaining the lab (Mani & Patvardhan, 2006). More precisely analyzed Achuthan and Murali (2015), the direct costs describe, for example, the equipment, software, consumables, and project staff, while the indirect costs are those related to the time spent, such as the development of the experiment, its validation, the room rental or the training and supervision of the teachers (Kara et al., 2010; Zhang et al., 2018; Zutin et al., 2010). To reduce these as much as possible, people talk about cost-effectiveness (Gruson, 2018) or cost-cutting strategies (Zutin et al., 2010) that try to reduce costs, for example, administration, maintenance, and training costs can be reduced by self-maintenance and automation techniques (Azad, 2020; Orduna et al., 2016). In general, these vary greatly by the type of lab; for virtual labs (simulations), maintenance costs and post-development efforts tend to be low (Orduna et al., 2016). When designing and developing the lab, the architecture should already be developed to minimize deployment costs (Villar-Martinez et al., 2019). The current literature on revenue enhancement for online labs is still limited. Revenue is determined by the performance effectiveness of lab resources and access revenue (Mani & Patvardhan, 2006; Zutin et al., 2010). Pricing models (Orduna et al., 2016) and Lab as a Service (Tawfik, Salzmann, et al., 2014) are seen as enablers for revenue and possible financial participation and grants as start-up funding (Azad, 2020). However, sustainable business models for online labs are currently only found in Orduna et al. (2016) and (Kammerlohr et al., 2021), both of which pursue the goal of the sharing economy.

4.2.4 Learning Support

The fourth requirement is learning support, or pedagogical effectiveness, whether and to what extent the online lab supports coursework (García-Zubía, 2021). As Kara et al. (2010) said, *"effective learning in engineering education could be achieved only by those approaches combining theoretical courses with laboratory"*. Not only does the lab support the experiment, but so does social coordination, the lab environment, and individual differences (Nickerson et al., 2007). We distinguish in learning environment, interactivity and realism, technical support and maintenance, and didactic support.

Learning environment describes the cognitive, affective, and psychomotor services that can be achieved in a lab (Lucca et al., 2004). Both the type of experiment, reconfigurability for additional services, the pedagogical model and framework, and the next generation online learning environment influence the learning environment. Tawfik et al. (2014) categorizes next-generation online learning environments into three areas: the semantic web and artificial intelligence, the web of things and the ubiquity of networked everyday objects, and the mashup of loosely coupled services. Lindsay et al. (2009) also summarize that many tradeoffs must be made to create the most effective learning environment within the constraints of available resources. A possible solution to this is demonstrated by Frank and Kapila (2017), by combining mobile devices with those of lab test benches, thereby creating a dynamic systems and control concept. The type of lab is divided into an observational experiment environment where only observation is possible, a fixed experiment environment where fixed parameters can be set, and an adaptive experiment environment where both the parameters and the environment can be changed remotely (Zutin et al., 2010). Operational control, similar to degree of freedom, describes the degree of control a student can exercise over the experimental design or the openness and creativity that are possible in an experiment (Mani & Patvardhan, 2006). This has a direct impact on the original intention of labs, whether it is possible in the experiment, for example, to learn from mistakes, conduct investigations, or thereby map a learning curve (Mani & Patvardhan, 2006; Morales-Menendez et al., 2019). Reconfigurability describes how easily these experiments can be modified, redesigned, and adapted to new processes to link them to additional services, learning objectives, or to integrate them into a new course (Lucca et al., 2004; Mani & Patvardhan, 2006; Tawfik, Salzmann, et al., 2014). Additionally, the lab should be extensible and configurable through various engaging media, such as text, audio, video, chats, forums, data, or web-based materials (Bencomo, 2004; Sullivan, 2003). The pedagogical models and frameworks define for online labs the setting and processes for teaching and assessing learning, such as competence-based learning, experiential learning, flipped classroom, or continuous assessment (Qu et al., 2019). These directly impact learning outcomes and the skills to be achieved. Learning outcomes are determined by the effectiveness of experimentation in learning (Mani & Patvardhan, 2006), where Achuthan and Murali (2015) proposed constructivist learning through visual and verbal learning. Skills are determined by expression such as difficulty, duration, and number of repetitions (Mani & Patvardhan, 2006). As described at the outset, the literature refers to next-generation online learning environments (Tawfik, Salzmann, et al., 2014). Here, the authors refer to the effective use of new technologies for teaching, such as augmented, virtual, mixed reality, and mobile devices, as well as learning analytics and gamification, with the aim of improving the experience of learning and teaching (Frank & Kapila, 2017; Yeung et al., 2010). In this context, Gruson (2018) describes smart digital labs using the acronym SMART (speed, metrics, automation, remote, technologies), which consist of the key elements of smart processes, integration of big data and real-time data management, automation, blockchain, Internet of Things, and improvement of user experiences.

Interactivity and realism mean that the environment must engage students' interest and motivation, whether they are using a real or simulated lab (Bencomo, 2004). A realistic simulation is a more effective learning experience (Lindsay et al., 2009), where the dynamics of the system and environment respond in real time to each action of the student (Bencomo, 2004). We distinguish between characteristics of authenticity and collaboration. Authenticity describes genuineness in the sense of originality. According to Morales-Menendez et al. (2019), this is achieved by linking students’ experiences to their everyday lives. The attractiveness of the system must be visually appealing to ensure the feeling of telepresence or immersion (Bencomo, 2004; Zhang et al., 2018). Furthermore, the system must be realistic, which describes how closely the experience in the lab resembles work in the real world (Mani & Patvardhan, 2006). Also referred to as practical realism (Bencomo, 2004) or inherent performance capabilities (Hacker, 2010), users need to know what is happening in the physical system and its environment at all times. Collaboration describes working together towards a common goal (Bruns et al., 2007), where this promotes both motivation and cognitive engagement (Morales-Menendez et al., 2019). According to Heradio et al. (2016), task completion should preferably be in collaboration with peers and regulated by learners. The literature emphasizes student interaction (Zutin et al., 2010), teamwork (Qu et al., 2019), and a sense of community (Sullivan, 2003).

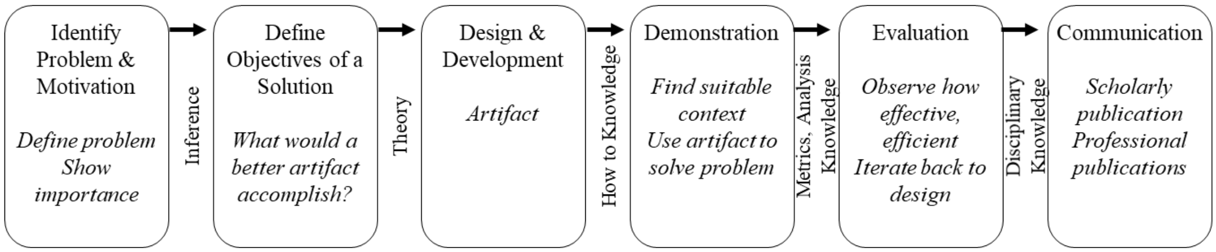
Technical support and maintenance describes the extent to which the lab operator has response capacities in the event of a failure of individual components or the entire lab (García-Zubía, 2021). An operations and maintenance concept that prevents failures and creates structures for optimal operation can help. We distinguish between technical documentation, qualified personnel, and real-time monitoring. A comprehensive technical documentation of all technical lab components and their interaction should be available which is up-to-date, self-explanatory, and complete and can be retrieved at any time. What is difficult today is finding qualified personnel available in the required volume and time, as financial resources are limited (Kara et al., 2010). Operational concepts such as 24x7 or on-call only are conceivable. Such concepts are essential for user confidence and secure operation, but are contrary to the goals of efficiency, where the use of fewer personnel is desired. Conceivable solutions range from a real-time monitoring system that provides continuously updated operational information (Gruson, 2018), to an exception handler that detects anomalies and restarts individual applications or the entire system (Ying & Zhu, 2004), to a prediction maintenance system that learns from historical and real-time maintenance data.

Didactic support describes whether and to what extent the teacher is able to understand, discuss or debate the didactic benefits of the lab, what means are provided to communicate this to students, and whether the lab facilitates the work of students and teachers in class (García-Zubía, 2021). We distinguish between e-learning material, which should be self-explanatory, the degree of interaction support provided by communication systems, and the availability of integration into a learning platform. E-learning material describes additional available information about the lab (Zutin et al., 2010), such as learning settings that easily and understandably familiarize with the physical lab environment and equipment (Lucca et al., 2004), supporting material or references such as user materials, student materials, teacher materials (Bencomo, 2004; Orduna et al., 2016), or further guidance for self-study (Ying & Zhu, 2004). Interaction support describes the extent to which student-faculty and student-student interaction is supported by the lab, e.g., through chats, video streams, or forums (Mani & Patvardhan, 2006). As described earlier, learning platforms are increasingly used by faculty to enhance student learning. A critical concern is the extent to which the lab supports learning progress in a learning platform so that all work materials can be organized in a single platform (Azad, 2020; García-Zubía, 2021).

4.3 Methodology

The theoretical perspective of the digital lab's transformational effectiveness literature assumes that criteria are subject to multiple truths and that these are determined by the subject matter and the underlying use case. Therefore, a constructivist approach based on multi-stakeholder interaction was used to gain insight and build knowledge about the effectiveness of the labs' digital transformation. To this end, the principles, practices, and procedures of the design science of information systems methodology (DSRM) by Peffers et al. (2007) were applied to determine the effectiveness criteria of a maturity model. The goals of the DSRM are to be consistent with previous literature, to follow a nominal research process model, and to use a mental model for representation and evaluation (Peffers et al., 2007). Therefore, this study applied the six process activities of the DSRM, illustrated in Figure 6, to develop and evaluate the maturity model as an artifact to measure the effectiveness of digital lab transformations.

Figure 6: DSRM Process Model, by Peffers et al. (2007, p. 54)



Activity one, *problem identification and motivation*, describes the lack of a maturity model for the effectiveness of digital lab transformation. Online labs can be used to be shared among each other, the organizational effectiveness for this is not currently surveyed. Initial steps of organizational aspects of online lab sharing have already been taken by the authors for this purpose. A platform business model for activating online lab sharing was created (Kammerlohr et al., 2021), and considerations for building initial and long-term trust between stakeholders as a critical challenge of a lab sharing platform were made (Kammerlohr & Paradice, 2022). These two organizational aspects are complemented by a maturity model that captures the effectiveness of organizational transformation in the lab and serves as a link between the business model and trust development**.** The second activity, *define objective*, is to create a maturity model with qualitative dimensions, items, and weights for online labs. This can be used by lab operators for design, implementation, or improvement and by users such as students for comparability to establish initial trust. The third activity, *design and development*, starts from the Scopus literature review found in Section 4.2. For the design, the literature was clustered into four dimensions, and research findings with numerous levels were collected in a mind map. A model was designed that included items at two levels per dimension, resulting in a maturity model with four dimensions, 18 level one items, and 38 level two items. The fourth activity, the *demonstration of the maturity model*, was demonstrated in a total of 11 case studies in expert workshops and expert interviews. A case study is a real online lab that has been tried and tested by the customer and is intended to provide retrospective accounts of real projects. These demonstrations were conducted at different online labs consisting of different lab types, different organizations, and different maturity levels of digital transformation. The fifth activity, *evaluation*, was conducted in two steps, the expert workshop described in Section 4.4 and the expert interviews described in Section 4.5. The iteration between workshop and interview aimed to reduce the subjectivity of the qualitative evaluation framework. The expert workshop was conducted with up to nine experts from a lab network, so that different viewpoints of the experts could be discussed and a balance between technical depth and practical benefit was achieved. Based on the results of the expert workshop, six expert interviews were conducted in a second step with seven experts based on their case studies. The targeted selection of experts made it possible to cover further depth, limitations, experiences and specific use cases. Finally, the sixth activity, *communication*, takes place in Sections 4.6 and 4.7, where the digital lab transformation maturity model is communicated and the benefits, results, limitations, but also further steps and generalization are discussed.

4.4 Expert Workshop to Develop the Maturity Model Concept

Based on the results of the literature review, a two-day, face-to-face expert workshop was held in the summer of 2021. The nine participants on the first day and eight on the second day were from two public universities and one research institution from Germany and Italy that operate a joint lab network. These experts are active professors or researchers and qualify as experts either by having research activity, identifiable by publications and public funding, or having conducted a digital lab transformation and being operators of online labs. The goal of the workshop was to a) validate the completeness of the maturity dimensions, b) align the maturity levels (low, medium, high) per item, and c) rank the maturity dimensions according to relevance and potential use cases. In preparation for the workshop, the maturity model was sent to participants with the task of reviewing the dimensions and items of effectiveness for completeness and requesting a weighting of the maturity dimensions and items. On the first day of the workshop, the results and comments on the preliminary work were discussed, such as the dimensions and items, the classification of the maturity dimensions, understanding of the potential use cases, and the definition of the maturity levels. On the second day, the maturity model was applied by the experts to six different case studies of online labs from the three organizations, all of which had different levels of maturity. The following results were obtained, first on the objectives, on the dimensions, elements and maturity levels, on the weighting and then on the application of the maturity model.

The *objective* of the maturity model in terms of added value for the user was discussed from different angles and many use cases were highlighted. One of them was whether the maturity model should be used for a general comparison between online labs, or as a reference model with best-in-class solutions of the maturity levels, or as a generally applicable solution for individual labs. For a comparison between labs, it was agreed that limitations are necessary from today's perspective, as the quality of the digital transformation of online labs is not the same and therefore cannot be compared and generalized in the maturity model. The possibility of creating a general maturity model or one for each type of lab was also discussed, for example, a specific maturity model for a simulation lab or a specific one for a real hardware lab. The experts felt that a general maturity model for all lab types would be more beneficial in terms of applicability and penetration. The discussion noted that there are too many different granulations of lab types, but the utility of different maturity models for lab types seemed low. The usefulness of a maturity reference model was confirmed but not pursued, as it was preferred to simplify the complex issues rather than further complicate them with best-in-class references. In conclusion, the experts unanimously agreed that a simplified maturity model for single-lab solutions that could be universally applied to all lab types should be pursued, as this would provide the greatest benefit. Participants were aware that this meant that some dimensions of the maturity model might be more or less relevant to certain types of labs and users, but that this limitation would have a positive impact on potential implementation and applicability. Therefore, this solution was addressed later in the process.

The *dimensions, items, and levels* of the maturity model for digital lab transformation were well received. However, participants wanted the model to be a stand-alone solution, a self-explanatory model with precisely defined dimensions and items in the model to enable a consistent understanding. This increases usability and reduces the required prior knowledge. Specifically, all dimensions and items and their associated maturity levels were discussed, questioned, and adjusted as needed based on the literature review. This resulted in no changes to the dimensions, but 13 changes to the items compared to the literature analysis, specifically eight changes/additions in wording, two mergers of individual items, and one addition of an item.

Within the universality and accessibility dimension, the wording of two items was changed to required client hardware (originally: machine resources) and technical support and maintenance at lab side (originally: technical support and maintenance). This change makes it clearer that the clients are meant as a resource, and that the technical support refers to the lab side. Within the user management dimension, the wording has been changed to personal dashboard and record store (originally: dashboard, learning analysis, experimental record store), with learning analytics removed from the user management dimension to better fit learning support. In addition, accessibility and availability have been combined into one dimension. Previously, these were separate items that were merged due to demarcation difficulties; now the element describes the time constraints. Finally, additions to the phrases security (client & server) (originally: security) and security (people) (originally: security) were added to this dimension. The additions in parentheses make the items more precise.

In the scalability and extensibility dimension, scalability was added alongside shareability. The experts felt this addition was necessary to emphasize the need for scalability; now scalability describes possible scaling and shareability describes organizational constraint. Within the same dimension, the terms certified (learning) material (originally: eLearning or industry standards) and certified (learning) services (originally: accreditation) were added. This brings to the forefront the regional certification limitations of the material and performance. Finally, the two items of cost and revenue have been merged in this dimension. This emphasizes the need to balance costs and revenues. In the learning support dimension, the wording interactivity (originally: collaborative) has been changed, giving more emphasis to the goal of constructive interaction within participants. Finally, the wording of the item system monitoring (originally: real-time monitoring) has been adapted by referring to the actual function as event or predictive. In the course of reviewing the dimensions and items, the maturity levels were jointly determined. The experts supported the proposal of five levels, where one describes lacking the attribute, three describes the state-of-the-art of the attribute, and five describes the leading edge of the attribute. In this context, two and four allow flexibility if an assessment cannot be directly assigned to an attribute.

The *weighting* of the items was surprisingly uniformly found to be unhelpful. First, the experts' results were collated, anonymized and any conspicuous differences in the proposed weighting factors were put up for discussion. However, the experts agreed that a weighting factor was not necessary because it was not a quality assessment. Moreover, a quality assessment would in turn increase the complexity of the model and limit the meaningfulness of the dimensions. The relative importance of the individual dimensions cannot be stated. Furthermore, from the experts' point of view, the ranking depends on the learning objectives and the concerns pursued in the lab and is therefore subjective. The model should still calculate the degrees of the dimensions (but unweighted) by calculating the average of the items on the dimensions. Again, it was emphasized that the model should simplify things, even if reality is not perfectly represented, that a simple model is used for this purpose. In the context of a specific project with several digital lab transformations, the experts believe that weights can be created if the goal is defined jointly, but not as a general model.

An *application to six online labs case studies* of the maturity model was conducted on the second day from three different organizations that belong to different lab types and are at different stages of digital transformation. First, it was found that online labs typically support multiple scenarios, such as a single student or multiple professional users, and thus have different levels of maturity. Accordingly, this scenario needs to be defined before the model can be applied. In the workshop, the following online lab scenarios could be tested in the maturity model: future students using the lab remotely, students using the lab remotely as coursework, students going through the lab as an exam performance remotely, professionals using the lab as simulation. In the course of using the model, all experts reported the valuable benefits of the developed maturity model. Thus, the practical benefits and applicability of the model could be proved in the expert workshop. However, one expert pointed out the limitation that there may be certain types of online labs for which the model is less suitable. Serious gaming labs were mentioned as an example, which are different from traditional online labs due to multiple lab scenarios that are rooted in modular and scenario-specific design. Serious gaming labs are designed for gamification and are one of the simulation lab types that have not undergone a digital transformation, but are developed directly with the goal of mimicking a real-world use case. That is, they are customized to each customer's needs, which is the business model, the labs are custom made and not developed for sharing. The expert explicitly emphasizes that this is a special scenario and that this does not invalidate the maturity model, but that some elements are less relevant for serious games labs. In this area, the expert suggests the use of maturity models developed specifically for serious games, such as the Game Maturity Model from KPMG (Boer et al., 2013).

The experts have received this section for approval and were asked to indicate possible change requests, the present text is the version approved by the experts.

4.5 Expert Interviews to Refine the Maturity Model

Six expert interviews were conducted between November 2021 and January 2022 with seven experts who had not participated in the workshop from Section 4.4. The maturity model was applied by the experts to a further five case studies (two experts dealt with one use case, one expert wanted to take a broader view of the maturity model and not apply it to one use case). Interviews were terminated after six interviews because no new insights were gained and saturation occurred. The seven experts have different titles and functions in the field of online labs and are listed in Table 5.

Table 5: Experts Title and Role

Expert	Title	Role
1	Co-founder, researcher	Lab manager
2	Professor, researcher	Lab manager
3	Professor, researcher	Lab manager
4	Assistant professor, researcher	Lab consultant
5	Professor, editor in chief	Researcher in various leading roles
6	Professor, researcher	Lab manager, project manager
7	Lecturer, researcher	Lab manager

The experts come from six different organizations in the USA, Spain, Germany and Austria. The experts were selected based on their expertise as expressed in active research projects, publications, participation in professional conferences, and the resulting likely fulfillment of the criteria for a capability. These criteria were derived from the expert workshops and the resulting potential constraints, focusing on the different types of labs, international applicability, and sustainable viability of online labs. First, the expected capabilities were identified by the authors through targeted research and then revealed to the experts during the interviews. In meeting the criteria, a distinction was made between core capabilities, non-core capabilities, and missing capabilities of the experts. Then, in the first part of the interview, the experts were asked to compare this expected capability with the experts' self-assessment. In total, 11 of the 56 expert capabilities were corrected in this way. The final expert capabilities can be found in Table 6, which shows the distribution of criteria fulfillment among the individual experts.

Table 6: Overview of the Capability Fulfillment of the Expert Criteria

Capability to review the model in terms of…	**Expert**						
	1	2	3	4	5	6	7
online lab types and functionalities,							
• for different lab types.	X	X	X	X	X	X	X
• for latest technical lab trends.		(X)	X	X	X	X	(X)
international online lab applicability,							
• can cover international differences.	X	X	(X)	X	X	(X)	X
• can cover differences of large and small labs.	X	X	X	(X)	(X)	(X)	X
sustainable viability of the online lab,							
• by newly or long established labs.	X	X	X	(X)	(X)	X	X
• by a profitable lab provider.	X	(X)	(X)	(X)	(X)		(X)
• by a lab operator who already shares.	(X)	X	X	X		(X)	X
• by a platform operator.	X	(X)	(X)				X

*(X) non-core capability.

Interviews were conducted via Zoom or Google Meet and lasted between 60 and 90 minutes. The model was provided to the experts in advance of the meeting. The experts first evaluate their own online labs as a case study for the maturity model, and then the following guiding questions were used in the discussion: a) where do you see the strengths and weaknesses of the model, b) which areas are not or insufficiently covered from your point of view, c) practical and reusable recommendations, how can the model help, and d) when should it be implemented in your opinion (product life cycle)? The experts then had to take on the role of the capabilities in Table 6 and evaluate the maturity model from this use case perspective.

When the *experts evaluated their own online labs* as a case study for the maturity model, the maturity model was quickly adopted; only the order of one dimension, additions in the naming of two items, and an addition in the naming of one item level were recommended, as follows. Within the trustability dimension, the order should be changed so that the initial trust elements are identified first (social features und reliability), followed by the long-term trust relationship phase. It was also recommended to change the wording of an item to long-term relationship stage (originally: relationship stage). The change is intended to introduce the user to the topic of trust in a more structured way. Furthermore, the experts recommended changing the wording of an item in the dimension learning support to interactivity with lab (originally: interactivity) in order to achieve a clearer distinction from the item interaction support. Finally, an addition to the level definition of the item reconfigurability in fully flexible in subject area (originally: fully flexible), since labs must always be operated in a context.

The *basic applicability of the maturity model* by the experts based on their own case studies first showed the strengths and weaknesses of the maturity model, the areas not or insufficiently covered, followed by the transfer to practice and reusable recommendations, and finally the timeline for applying the model in the product life cycle. As *strengths* of the maturity model, the experts mentioned the clear overview covering all areas, the comprehensiveness with good questions and the level of detail for lab providers/developers. The maturity model is a basis for different things, it creates comparability, enables trends to be derived and is a motivator or guide for further development. Furthermore, the experts confirmed that the maturity model has a community, is therefore relevant and that nothing comparable currently exists. The *weaknesses* arise from the nature of the maturity model and the technical limitations. The maturity model is used by the user to assess their lab use cases according to their own specifications, which risks preventing people with less experience from providing objective answers. In addition, the high degree of abstraction of the maturity model can lead to a bias in the representation. Also, some things may be more or less relevant depending on the perspective of the user, such as reliability or documentation for the professor or student. In addition, the mutual interactions are not apparent in the maturity model for the use cases; for example, how does a purely static lab affect learning success? Finally, from a technical perspective, it is difficult to distinguish between lab and remote lab management system or platform services. Online labs are often integrated into platforms, so platform functions might be confused with lab functions in some use cases, or some functions might be provided by the platform. Two experts did not point out any weaknesses in the maturity model.

As *areas for improvement*, the experts do not see any area that is insufficiently covered or overly relevant for specific use cases. However, the maturity model could address other areas in more depth, such as reflecting the "open" movement/standard such as open software and hardware, or be more specific about certain business models (e.g., pay-per-use or freemium), or it could further deepen liability in one dimension. To one expert, some areas of the maturity model are very important, such as standardization, pedagogical framework, or interactivity; highlighting these could emphasize their relevance for use cases. Other experts point to impulses in which the maturity model could be further developed to provide more perspectives. The maturity model could be adapted to different personas, like users, teachers, lab managers, lab providers, or consultants, to get different development perspectives. In addition, examples or case study references would help to understand the maturity levels in more detail and the underlying effort required for a level increase. Also, behind each organizational maturity level is a technical and didactic effort that needs to be pointed out. In a similar vein is the idea of linking direct suggestions for level improvement to maturity levels.

For the *practical and reusable recommendations*, the experts first describe what the maturity model is suitable for and how, and then provide recommendations for practical application. The maturity model is very suitable for self-assessment and as a food for thought that shows possible adaptations (suggestions for a new system) of use cases. One expert became aware of three points through the evaluation of his own online lab by the maturity model that he would like to deepen in his case study; the maturity model drew his attention to this. As a practical suggestion, one expert recommended using the maturity model as a basis or guide for discussion in a group, which can reduce subjectivity due to the different perspectives. In addition, three experts rated the maturity model as exciting and helpful for the community in practical application; it could be used as a kind of case study reference model for the community. One expert sees the maturity model as the basis for a certification process for online labs in the community. In his role as expert and editor-in-chief, he would like to contribute to using this maturity model as a standardization model to increase the maturity level of labs and certify them. This idea of using the maturity model as a standardization model has been taken up independently by other experts. In contrast, one expert estimates the maturity model to be less useful for lab selection (less for sales or user acquisition), but more for lab comparison or self-assessment, as it is a qualitative model. The experts cite the comparability between two different labs, for example between the current and future state or between two lab types, as a challenge in practice. In addition, the recommendations for action to be derived, the transfer to the maturity model, and the bridge between maturity model and reality are seen as difficulties. One expert also pointed out that in practice there is a conflict between universality (many user groups) and capability (deep investigation); if an online lab is powerful, other characteristics are lost.

The point in the *life cycle* should provide information about the phase in which the maturity model should be applied to use cases. Five experts agree that the maturity model is helpful in all phases of the life cycle. Two experts indicated that it should be used as a checklist in the planning and start-up phases of use cases, with one expert adding that the maturity model should be used as a stimulus for reaching new audiences (so that the lab does not become obsolete), and as a promotional tool for commercialization in the maturity phase. The expert sees the maturity model as a kind of speedometer that shows strengths and weaknesses and points to improvements. The maturity model could be a kind of marketing opportunity, and if the maturity level is high, it can be a kind of trust criterion (if it is universally valid or certified/accredited). As an impetus for this, he suggests proceeding on the basis of an accreditation catalog. He also suggests the use of a spider diagram to better visualize strengths and weaknesses of case studies. One expert supports the idea of certification, this one sees the benefit in the maturity phase to compare and certify labs. Two experts also suggest introducing the maturity model as an iterative process (perhaps every year when in active development) that opens up new (open) discussions within the community. One expert sees the added value of the maturity model mainly in the initial phase to find out what should be addressed in the future and later for self-assessment to identify opportunities for improvement. Another expert described that the planning phase is too early for inexperienced users because a high level of experience is required to understand the implications of the maturity model; therefore, for inexperienced users, the model is ideal when the lab is in the growth phase and they have gained their own experience.

In the next part, the experts had to take the role of their *capabilities and evaluate the maturity model* from this use case perspective. To this end, we first highlighted the added value of the maturity model for online lab types and functionalities, then for international applicability, and finally for online lab sustainability. All experts agree that the maturity model covers the *different online lab types and functionalities*, one expert adds that the model can be easily applied to all use cases, even outside the engineering discipline. However, two experts added that some lab types within the maturity model naturally have lower maturity level, such as scalability of the remote lab or realism of the simulation lab. One of them points out that the maturity model cannot be used for comparisons between different types of labs, like between simulations and remote labs, while a comparison between two remote labs would be useful. One expert notes that the maturity model would also be valuable to capture specific lab characteristics/types, such as prerecorded experiments. Next, all experts agreed that the *latest technical trends* of labs can be represented in the maturity model. However, one expert added that he is currently investigating the reusability (compatibility) of labs, which makes it clear that the maturity model is driven by external innovation and is therefore subject to change. Regarding the *international applicability of the online lab*, all experts confirm that the maturity model covers international differences in use cases because the model is generic/abstract. All experts also agree that the maturity model can *cover the differences between large and small labs*. One expert notes that for small labs, some of the dimensions of the maturity model may be less relevant or difficult to measure. For example, if you have a small lab use case, you think you can scale it, but you don't have experience with it. The same is true for safety: you think you're good at it, but when you've done it better, you have a different idea. One expert therefore thinks that a reduced maturity model variant could be useful for small labs. Finally, the experts evaluated the maturity model in terms of the *sustainable viability of online labs*. First, all experts confirmed that they are able to test the maturity model for new or long-standing labs and that they do not see any limitations of the model in the different use case life cycles. One expert added that the maturity model can be used as a starting point to explore whether sustainability is beneficial in small and large labs. From the perspective of the profitable lab provider, one expert had to abstain, one disagreed, but five experts were able to confirm the usefulness of the maturity model for profitable lab providers. Of these, one expert added that the maturity model was specifically useful for lab providers and less practical for researchers. Another expert added that the use of the maturity model could be a unique selling point, as the model could be helpful in marketing and advertising case studies. An expert sees no benefit in the maturity model for the profitable lab provider because the problems are much deeper than what can be achieved with a general model, but for the expert there will never be a model that can cover this. According to this expert, the maturity model could be an indicator to ask the deeper questions. Subsequently, from the point of view of the lab operator who already shares, all the experts emphasized the usefulness of the maturity model, they added that the model helps, important questions are raised in the model, and helps to become more efficient. Finally, the experts were asked for the platform operator's view. One expert abstained, while all others confirmed the advantages of the maturity model from the platform operator's point of view. Two experts underlined the advantages of this maturity model with "strong!", the model questions are well posed and relevant. Another sees it as a quality standard and marketing instrument.

Finally, the expert interview was concluded and the experts had the opportunity to make *further comments on the maturity model*. One expert confirmed that trust is very important to him, but believes that two trust approaches are required in his view: 1) what we saw in the maturity model, and 2) a technical test of whether we can trust (and they are not incompatible) a case study, for example, a (technical) test of whether the lab has been technically trustworthy in the past, such as accessibility, backup, technical insurance, or automation. Another expert is concerned that not all users, such as students, understand all the meanings of the maturity model, its metrics, and their implications. The student would likely resort to less academic tools, for example, feedback from a fellow student. However, from the operator's perspective, this maturity model could be motivating. One expert makes two general additions from his point of view: 1) The lack of sustainability of the labs is due to the lack of standardization and homogenization, and the financial pressure is not high enough to increase profitability. 2) A core element for the success of the labs is (international) certification, for which the maturity model is perfect (ideal instrument), but the question is who will do and finance this. Finally, one expert points out a possible constraint: Universities might be subject to a natural constraint (yet to be verified) in some regions, as they cannot generate revenues or can only generate revenues indirectly.

4.6 Discussion and Contribution

Returning to the research questions, can the effectiveness of digital lab transformation be adequately described in a maturity model and thus used as a tool to support the sharing economy? The maturity model developed has reached a necessary level of maturity between the literature and the two expert iterations, with saturation occurring most recently in the interviews. It can be inferred that the model now effectively maps the dimensions, items and levels of digital lab transformation. From the perspective of the experts and the authors, the model can thus fulfill three practical objectives that support the sharing economy: 1) to establish comparability of the effectiveness of the digital transformation of labs, 2) to provide lab operators with a guide for (further) transformation, and 3) to build initial trust among lab users. In addition, the model contributes to the literature on digital lab transformation by capturing, describing, structuring, and assessing the relevant dimensions, items and levels. In addition, the maturity model was applied to 11 case studies in the STEM domain. These case studies were divided into 5 remote labs, 3 simulation labs and 3 AR/VR labs. This allowed a total of 407 data values to be collected for the maturity model, with scores of 6xN/A, 64x1, 41x2, 126x3, 75x4, 95x5. The case studies differ in terms of lab type, functionalities, technical lab trends, international differences, size of users, whether new or long-established, profitability, and interchangeability. These assessments are discussed in detail below, beginning with the findings of the 11 case studies, contributions to the literature and implications for digital lab transformation practice, and limitations of the research.

At the maturity model level, the results of the case studies show (Appendix D) 1) that the scale of one to five was fully utilized, 2) that the four dimensions of the maturity model are comparatively balanced, and, 3) that the four dimensions corresponds very well to the state-of-the-art attributes for supporting digital transformation in the lab. The four dimensions of the 11 case studies have a mean score of 3.2, specifically for universality and accessibility (3.3), user management (3.3), scalability and extensibility (2.7), and learning support (3.5). This shows that the dimension learning support is 0.8 points apart compared to scalability and extensibility. It can be argued that this dimension has already been studied many times in practice and theory and therefore has a higher degree of application. On the other hand, this also shows that the aspect of scalability and extensibility is not yet sufficiently taken into account in practice, since the value is 0.8 points lower. Besides, the dimension installation stands out in the evaluation of the case studies with a mean value of 4.4, the lab managers seem to be aware that a low threshold and thus a low installation (e.g. browser-based) is important for the use of the labs. Some of the points raised by the experts are also reflected in the figures from the case studies. In the dimension of user management, it is apparent that in conventional labs this is largely carried out in practice by a remote lab management system and not by the lab itself. For example, item accounting, with a mean of 2.1, is not supported by the lab itself in all case studies, but when it is, it is often supported by an external system. In addition, the figures are consistent with expert opinions that labs in earlier lifecycle phases have a lower degree of maturity, which was to be expected. Surprisingly, only one of the 11 case studies can show that costs are lower than revenues, with a mean of 1.4, but this is consistent with the experts' experience. However, this finding reflects the current problem of the use cases, where labs are established without a successful business model and attempts are made to operate them with budgetary or public funding. This maturity model can help address the right questions early on for lab operators to achieve sustainability through further revenue generation. Finally, with a mean score of 2.0, none of the case studies have certifications beyond the department. Both the authors and the experts in the interviews see the enormous benefits, but point to the challenges of practical implementation in an international environment with non-standardized education systems. How can it be achieved that a successfully completed online lab course is accepted and accredited by local educational institutions?

The *contribution to the literature* and *implications for transformation practice* are described as follows. This paper relates to the research on digital lab transformation, on which extensive knowledge on didactics and technology is already described in the literature. The paper therefore focuses on the research gap of the organizational view of digital lab transformation (Uckelmann, 2012) and online lab sharing (Orduna et al., 2016). We respond to this research gap with a structured maturity model comprising four dimensions, 18 first-level items, and 38 second-level items. It describes the organizational view of digital lab transformation and provides an artifact for both the user and the lab operator to facilitate online lab sharing by establishing initial trust and guidelines for further lab transformation. New scientific activities are emerging from the maturity model; we distinguish between possible further developments in the model itself and further developments outside the model. The maturity model itself will need to evolve further in dimensions, levels, and definitions to reflect the latest research findings. In addition, the maturity model could be extended for individual lab types to more comprehensively address the specifics of a use case and allow for comparability between different lab types. Furthermore, characteristics between online lab and platform services could be included in the maturity model so that stand-alone labs and labs integrated into a platform become comparable. Further, the maturity model could be developed for different users, such as students or professors, which would clarify the added value between maturity levels from the user perspective per dimension. Finally, evidence could be provided that individual use case dimensions and levels influence each other, for example, high levels of support staff on costs.

At the other end, further developments beyond the maturity model could take place. A global reference database could be built to showcase case studies with associated maturity levels throughout the maturity model to provide confidence and transparency to the user. This could also be based on an accreditation catalog. In addition, lab type-specific limitations should be surveyed based on practical experience, such as serious game labs that have not undergone digital transformation or do not support the sharing economy. Finally, the question of how each maturity level can be used and developed to have a positive impact on sustainability could be explored, such as the impact of trustworthiness on business model sustainability based on Coase's (1937) and Williamson's (1993) transaction cost theory.

The *limitations of the research* result from the DSRM methodology itself (Peffers et al., 2007), that is, the fifth activity of iterative expert evaluation. First, it was possible to collect mainly qualitative data that allowed for a more accurate assessment of context and expectations. Unfortunately, however, it was not possible to implement a quantitative approach, as the literature increasingly focuses on characteristics that cannot be measured accurately. In addition, no expert was evaluated across both evaluation stages (expert interview & workshop), which meant that no outsider evaluation of the maturity model development process could take place. Also, experts were selected based on their expected capabilities, but the evaluation was reviewed by the experts themselves as part of the survey process. As a result, there could be a discrepancy between the required and actual capabilities. Furthermore, the capability of the profitable lab operator as well as the platform operator could only be rated as a core capability by one/two expert, who, however, did not express any objections in both dimensions. The reason for this is that the experts in the community have little experience or that they are reluctant to take on their expert role. In addition, all communication with the experts was conducted in English, which could have led to linguistic misunderstandings, as English is not the native language of the experts and authors. Finally, experts from different regions were considered who did not express any regional concerns, but this cannot be generalized to all regions.

4.7 Conclusion and Future Work

Our results promise a maturity model that provides tested results through the DSRM research methodology. The digital lab transformation maturity model can be used to develop a digital roadmap that helps online labs increase their effectiveness and evolve into a suitable sharing economy lab. In addition, the model helps companies determine what stage they are at in their transformation to an effective sharing economy lab. It assesses the transformation of the dimensions of universality and accessibility, user management, scalability and extensibility, and learning support. Furthermore, the maturity model enables comparability of labs at the level of lab type, dimensions, and items, which can be used, for example, to distinguish labs on sharing platforms. These results are based on a literature review in which an initial maturity model was developed using a mind map, which was finally matured in two expert integrations and applied by them to their total of 11 case studies. The results of the two expert iterations show that the maturity model is universally applicable, even beyond engineering and manufacturing applications, contains a clear overview that covers all areas, and is still comprehensive with good questions and a good level of detail. It creates comparability, allows trends to be derived, and is a guide for further development. Risks in using the maturity model are the subjective assessment by users, which is not subject to quantitative data, creating the risk that people with less experience cannot provide objective answers. In addition, the high degree of abstraction of the maturity model may lead to a bias in the representation. Suggestions for improvement were made, all of which the authors felt went beyond the goal of the current maturity model and are considered future work. Finally, it was confirmed that the maturity model is suitable for different online lab types and functionalities, latest technical trends, international applicability of the online lab, and for the differences between large and small labs. Thereby, the use of the maturity model for the sustainable viability of the online lab was confirmed from the perspective of new or long-standing labs, profitable lab providers, lab operators, and for platform operators.

In the *practical application* of the maturity model (Appendix B), it is recommended to have the model applied by thematically familiar users who are familiar with the dimensions of the model and the natural limiters of the different lab types. Alternatively, it is recommended to become familiar with the subject matter, e.g., through an extensive literature search based on Section 4.2, or to consult an experienced user. In practice, it has also been shown that this maturity model benefits from further perspectives, for example, through application in (small) groups. The maturity model can be applied at all stages of a lab's life cycle and, if necessary, can be used iteratively at all stages. At the beginning, a specific lab user scenario should be described in more detail and recorded in the maturity model if the lab covers different scenarios, e.g., several students must go through the lab remotely as an exam performance. It is recommended to go through the dimensions of the maturity model from top to bottom. In practice, it has been shown that ambiguities become obsolete in the course of application or are described more broadly in the definitions of the maturity model (Appendix C). When choosing maturity levels, it can be helpful to record the rationale for the level through a commentary, which can increase traceability. Once all lab levels are described in the maturity model, it is recommended to analyze individual outliers in more detail and discuss the conclusions for sharing. It can be helpful if this is shown in color or by a graph such as a spider diagram. Finally, short-, medium- and long-term recommendations for action of the lab can be derived from this, which may initially require far-reaching considerations. It is also conceivable to apply the maturity model again with different action alternatives in order to make the effects on the dimensions transparent. If possible, the results of the case study can now be shared in the community and alternative courses of action reflected upon.

As *future work*, we mainly see the penetration of the maturity model in practice and the further development and harmonization of the current lab transformation literatures between didactics, technology and organization. For the next steps in practice, we first see the participation and exchange of the relevant engineering and manufacturing education community to initiate a standardization and certification process. During the expert interviews, initial measures could be taken to this end. The goal is to reach as large an audience as possible for the maturity model and to collect a lot of feedback, impulses and references. Once a critical mass is reached, the maturity model could be modified for different types of labs. Looking at the further steps in the literature on digital lab transformation, we find that the three areas of didactics, technology and organization should be linked and harmonized. This should provide the user with a holistic and user-specific perspective on the transformation and also include the idea of linking the impact of maturity improvement with the impact on didactics and technology.

4.8 Acknowledgements

This work has been funded by the Federal Ministry of Education and Research (BMBF), Germany under the funding code 16DHB2112. The responsibility for the content of this publication lies with the authors.

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Chapter 5

5 Dissertation Conclusion

The digital transformation is taking place in education and research, and as this dissertation points out, now also in academic labs. This dissertation contributes to knowledge about shared infrastructures and digital transformation in theory and practice. Returning to the research questions, I conclude that this research has provided an overview of the role of trust in business and maturity model development based on three studies of shared digital labs. Specifically, it defines a business model that promotes sustainability by enabling online lab sharing, with defined success criteria and functional requirements, validated through industry comparisons, stakeholder interviews and surveys. A maturity model, evaluated in expert workshop and expert interviews, has been developed that can determine the effectiveness of digital lab transformation. And, a systems view of trust as a key element for platform business was constructed to identify gaps and opportunities for research and practice that serve as a basis for considering trust in the maturity model.

The first paper presents a business model for digital labs to promote sharing in network organizations. Using the Design Science Research Methodology (DSRM) in information systems by Peffers et al. (2007), a multi-sided platform was created and evaluated as a sustainable business model (BM). Developing a successful business model requires a BM definition, framework, and well-chosen taxonomy. The BM definition was able to provide good overview about the components and how value is created, delivered, and captured. The Business Model Canvas supplemented the missing visualization and interaction. In addition, the Platform Canvas helped highlight the relationships, functions, and issues between framework elements. Further, a multi-sided platform should meet the following functional requirements: customers expect valuable content, ease of use, affordable service, access to otherwise inaccessible materials and devices, and customer support. The benefits of a platform must be demonstrated over direct access, and the actual benefits are the selling point. Finally, the system and platform must be trustworthy, for which trust-building organizational measures are required. Among the paper's findings are that digital labs are becoming increasingly important, that there is an emerging trend from product- to service-oriented solutions, that a lab-sharing marketplace should provide targeted offerings for teaching and learning, and that industry customers and students are showing interest in educational content for digital labs. The willingness to pay on the part of students and industry is there, but for students, the discussion about who should pay for education remains fundamental in nature. In addition, industry customers point to fears of intellectual property loss and security risks. It has been shown how a sustainable business model for digital labs encourages lab sharing. As a result, universities can offer a better curriculum, faculty have more opportunities for quality education, and students have access to more lab environments.

In the second paper, it is shown that trust is something we encounter every day in our personal lives, but is increasingly important in technology-based transactions because traditional interpersonal trust factors cannot be applied as usual. A comprehensive overview of trust research, both from a non-technological and technological perspective, was presented to highlight gaps and opportunities for research and practice. Because trust is a very complex construct, an overview of the history of non-technological trust was first presented. This overview is organized into the context of personal, professional, and organizational relationships and addresses initial trust and the long-term evolution of trust. An overview of existing technology-based trust studies in the information systems research literature was then provided. Derived from this, it is shown where gaps in research and practice exist and what opportunities exist for future studies on technology-based trust by striking a balance between acquired and practical relevance. One finding for the lab sharing was that initial trust is already being used in a variety of contexts, but that the long-term development of trust and its implications have not yet been considered. The long-term trust relationship is a fundamental requirement for the existence and development of many platform business models, as the multi-sided platform showed. Platforms play an important role because they can reduce transaction costs (Williamson, 1993) between participants and because they are powerful digital business models that are adaptable and able to manage complexity, scale quickly, and create value (Abdelkafi et al., 2019). Finally, the paper explored the question of what technology can do in this area to encourage, reward, and cultivate the long-term development of the conditions necessary for trust. The third paper answered this question using the maturity model, which promotes long-term trust and initial trust in digital lab transformation. In turn, the business model from paper 1 can promote this level of trust in the maturity model by reducing transaction costs between actors.

The third paper presents a maturity model for the effectiveness of digital lab transformation. The model fulfills three practical objectives: 1) to establish comparability of digital lab transformation effectiveness, 2) to provide lab operators with a guide for (further) transformation, and 3) to build initial trust among lab users, drawing on the findings of the second paper. Furthermore, the maturity model contributes to the literature on digital lab transformation by capturing, describing, structuring, and assessing relevant dimensions, elements, and stages. For this purpose, the Design Science Research Methodology (Peffers et al., 2007) of information systems was applied and the associated six process steps were followed. The resulting maturity model artifact for digital lab transformation effectiveness was based on a structured literature review and evaluated through an expert workshop and expert interviews based on 11 case studies. Interactions with the experts resulted in confirmed potential maturity model objectives, strengths and weaknesses, areas for improvement, and practical and reusable recommendations. Finally, based on the expert capabilities, the added value of the maturity model for online lab types and functionalities, the international applicability of the online lab, and the sustainability of the online labs were highlighted. The maturity model takes into account both initial trust and long-term trust between stakeholders, which can ultimately serve as the basis for the business model. This demonstrates how trust can influence the development of business models and maturity models to support lab sharing.

All dissertations are limited in scope. In these studies, limitations arise from differences in the education system, such as regional differences in willingness to pay for education and the degree of digitalization. One problematic issue is willingness to pay; traditionally, education in Europe has been free. Students accept that the cost of a digital lab must be paid, but there is considerable dispute about whether the state, the university, or the students themselves should pay for it. Another limitation is the language and cultural differences that affect the type of education (practical vs. theoretical) and the level of education (BA, MS, PHD). In addition, regional taxes and public sector billing may impose limitations. Finally, it should be noted that English is not my native language, which may have led to misunderstandings or inaccuracies in interpretation.

However, this work also makes contributions that can be transferred. Generalizations can be made to related application areas, such as vocational training, but also to broader areas, such as shared infrastructures and digital transformation. The business model can serve as a model for areas where the concept of shared resources can be applied, such as research facilities for industry and research, space utilization models, or mobility concepts. As we have seen in the presented business model, by moving to shared resources, parts of the value creation can be taken over by the community, thus creating (financial) synergies. Additionally, the identified success criteria and functional requirements can help to be successful with this. For building trust in communities and in new technologies, the interpersonal and technology-based trust studied provides insights. This is about the meaning of trust and how trust can be used to increase it in a community and in a technology to promote and scale exchange. Furthermore, what trust paradoxes can occur. It is also about areas of trying to build a long-term relationship that goes beyond a one-time contact. Finally, the effectiveness of digital transformation, can be generalized to digital infrastructure as an approach to achieving sustainability for government agencies, universities, businesses, citizens and communities. Specific to the current area of online labs, one expert suggested that the maturity model could serve as the basis for a standardized assessment for all labs or as a tool for a certification process for labs. It could also serve as a starting point for harmonizing lab literature on didactics, technology, and organization.

Nevertheless, caution is required when putting the findings into practice. As indicated in the second lifecycle phases (dynamics) of the multi-sided platform, the platform and the associated ecosystem, such as the maturity model and trust mechanisms, should be further developed depending on the current situation (Otto & Jarke, 2019). To keep the platform attractive to customers, further aspects and trust-building mechanisms may be required, which I divide into central services, individual services, and community services. Central services refer to applications that are offered centrally on the marketplace, e.g., to improve matching. Specifically, a cooperative resource management system is envisioned, from which a common booking and billing process, work characteristics and resources, and common and standardized terms of use emerge. Additionally, a booking system that is able to cover the different needs of user roles, such as a recurring event for a lecture series would be beneficial. Linked to this should be a flexible billing system on a transaction basis to be able to map the levels of trust described, individual but also standardized, national and international, billing for companies and universities. Individual services are services that the marketplace provides on an individual basis, such as lab didactic or transformational services, research services, or the sale of processed research data. Community services are actions taken to build and sustain the community as an ecosystem around the marketplace. Simple things like a shared vision or mission statement can help, but so can conferences, awards, badges linked to learning pathways to make learning success visible to the outside world, or individual advertising of job openings or research contracts, all within the context of a trusted environment.

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Appendix

Appendix A: Publications Directly Used in This Dissertation

REV (Conference on Remote Engineering and Virtual Instrumentation)

[1] Reverberi, **Kammerlohr**, Esposito, Ghorpade, Romagnoli, & Uckelmann (2022). Billing and Booking System for Distributed IoT Laboratories. REV 2022. *Accepted*.

[2] **Kammerlohr**, Paradice, Hauge, & Duin (2022). *Towards the Operationalization of Trust Relationships in Networked Organizations*. In Auer, Bhimavaram, & Yue (Eds.), Online Engineering and Society 4.0, REV 2021. Springer International Publishing. https://doi.org/10.1007/978-3-030-82529-4_25

[3] **Kammerlohr**, Pfeiffer, & Uckelmann (2021). *Digital Laboratories for Educating the IoT-Generation Heatmap for Digital Lab Competences*. In Auer & May (Eds.), Cross Reality and Data Science in Engineering, REV 2020. Springer. https://doi.org/10.1007/978-3-030-52575-0_1

PRO-VE (Conference on Virtual Enterprises)

[4] **Kammerlohr**, Duin, Baalsrud Hauge, & Tany (2021). *Getting Collaborative Networks Sustainable: Drivers and Barriers Within a Digital Laboratories Network*. In Camarinha-Matos, Boucher, & Afsarmanesh (Eds.), Smart and Sustainable Collaborative Networks 4.0, PRO-VE 2021. Springer International Publishing. https://doi.org/10.1007/978-3-030-85969-5_3

[5] Baalsrud Hauge, **Kammerlohr**, Göbl, & Duin (2019). *Influence of Trust Factors on Shared Laboratory Resources in a Distributed Environment*. In Camarinha-Matos, Afsarmanesh & Antonelli (Eds.), Collaborative Networks and Digital Transformation, PRO-VE 2019. Springer International Publishing. https://doi.org/10.1007/978-3-030-28464-0_55

Summer School (Conference on Industrial Systems Engineering)

[6] Bisaschi, Esposito, **Kammerlohr**, Reverberi, Rizzi, & Romagnoli (2021). *Business Model validation for a marketplace of lab network initiatives*. In Proceedings of the 26th Summer School “Francesco Turco” – Industrial Systems Engineering.

[7] Esposito, **Kammerlohr**, & Romagnoli (2020). *A new 3d model to define laboratory services*. In Proceedings of the 25th Summer School "Francesco Turco" – Industrial Systems Engineering.

Other

[8] **Kammerlohr**, & Paradice (2022). *Fundamental Organizational Aspects of Shared Lab-Networks: Trust, Business- and Maturity-Model Considerations in DigiLab4U.* Online-Labs in Education Conference. *Accepted*.

[9] **Kammerlohr**, Uckelmann, & Baalsrud Hauge (2021). *A Multi-Sided Platform to Activate the Sharing of Digital Labs*. International Journal of Online Engineering (IJOE), 17(11), 4–33. https://doi.org/10.3991/ijoe.v17i11.25183

[10] Baalsrud Hauge, Duin, **Kammerlohr**, & Göbl (2020). *Using a Participatory Design Approach for Adapting an Existing Game Scenario – Challenges and Opportunities*. In Ma, Fletcher, Göbel, Baalsrud Hauge & Marsh (Eds.), Serious Games, JCSG 2020. Springer. https://doi.org/10.1007/978-3-030-61814-8_16

[11] Höehner, Rodewald, Mints, & **Kammerlohr** (2019). *The next step of digital laboratories: Connecting real and virtual world*. In Jorge, Glencross, Spencer, Mitchell, Kim, Narumi & van Eyken (Eds.), Virtual-Reality Continuum and its Applications in Industry. ACM Press. https://doi.org/10.1145/3359997.3365727

Appendix B: Digital Laboratory Transformation Maturity Model

Maturity dimensions	Maturity levels				
	Lack of attributes supporting digital lab transformation		**State-of-the-art attributes** supporting digital lab transformation		**Leading edge attributes** supporting digital lab transformation
	1	2	**3**	4	**5**
Universality and accessibility					
Universality and accessibility					
Multi-platform client	Tied to a single platform		Selected platforms are supported		Most platforms are supported
Installation					
Installation and use	Expert required for installation		Some effort required		Turnkey
Integration	Expert required for integration		Some effort required		Turnkey
Interface					
Real looking GUI	Descriptive reality		Reality abstraction		True to reality
Interface adaptability	Rigid interface		Semi-configurable interface		Configurable interface
Efficiency					
Required client hardware	Powerful clients		Average clients		All common client supported
Network resources	Fast network required		Average network required		Low-bandwidth
Technical support & maintenance at lab side	Always required		Specific cases only		Just in case of error
Trustability					
Social features	Not available		Star ranking and comments		Social features promote trust by known person
Reliability	No experience for reliability recognizable		Partly or indirect positive experience		Positive experience
Long-term relationship stage	Transitional stage 0: calculus-based trust		Transitional stage 1: knowledge-based trust		Transitional stage 2: identification-based trust
User management					
Management of usernames and password					
User's authentication	Must be created by admin		Self-registration		Access via existing access data
Maintain authentication and access right	Not maintained		Manual effort		Automated
Personal learning environment					
Personal dashboard and record store	Not available		Partially available		Pedagogical effectiveness is promoted
Queue & booking management					
Accessibility & availability	Heavy time constraints		Flexible time constraints		Permanently available
Accounting	Not available		Available		Fully integrated
Safety and security					
Security (client & server)	Low system security		Medium system security		High system security
Safety (people)	Safety risk exists		Operational safety		Supporting safety systems
Scalability and extensibility					
Audience					
Information about lab	Not available		Standard		Exhaustive lab information
Diversity of audience	Single audience		Selected audiences		All audiences
Extensibility					
Adaptability & interoperability	Not available		Standardized architecture		Adaptive lab system
Scalability					
Scalability	Not scalable		Limited scalable		Highly scalable
Shareability	Limited to organizational units		Inter-organizational		Not restricted
Certification					
Certified (learning) material	Not available		National		International
Certified (learning) achievements	Not available		National		International
Price and sustainability					
Cost & revenue	Cost higher than revenue		Cost equal to revenue		Cost lower than revenue
Learning support					
Learning environment					
Type of experiment	Observational		Adaptive		Real-time interactive
Reconfigurability	Not configurable		Limited possibility		Full flexible in subject area
Pedagogical framework	Not available		One pedagogical framework		Multiple pedagogical frameworks
Interactivity and realism					
Authenticity	Unnatural		Realistic learning experience		Improved practical realism
Interactivity with lab	Not available		Reactive interactivity		Constructive interactivity
Technical support and maintenance					
Technical documentation	Not available		Comprehensive available		Supportive available
Supportive staff	Not available		General support		Individual support
System monitoring	Not available		Event triggered		Predictive maintenance

Didactic support					
E-learning material	Not available		Multimedia material		Interactive material
Interaction support	Not available		Rudimental support		Community support
Learning platform	Not available		Tailored integration		Standard interfaces for learning platform

Appendix C: Definitions Digital Laboratory Transformation Maturity Model

Maturity dimensions	Definition
Universality and accessibility	Whether and how a lab is accessible to the user in any technological scenario, referring to the original design of the experiment.
Universality and accessibility	Universality describes platform independence and thus ease of access.
Multi-platform client	Accessibility regardless of platform, device or operating system.
Installation	Installation considers both the installation itself and the integration with a third-party system.
Installation	The extent / effort for installation within third-party system.
Integration	The extent / effort for integration within third-party system.
Interface	Interface to the experiment should replicate the working environment of the real lab.
Real looking GUI	Whether realistic-looking graphical user interface (GUI) is used to give the user the feeling of working in a real lab.
Interface adaptability	The degree the interface can be customized to the needs of the user.
Efficiency	The factor of resources required, both technical and human, with the aim of minimizing the use of resources without compromising the quality of the experiment.
Required client hardware	The extent and duration of client hardware required.
Network resources	The extent and duration of network resources required.
Technical support and maintenance at lab side	The extent and duration of technical support and maintenance at lab side required.
Trustability	Trustability refers to the institutions and their abilities to ensure the availability of the labs.
Relationship stage	Reflects the stage of trust evolution during the parties' interaction.
Social features	Social identifiers as trusted third parties, such as rating resources, adding comments or tags.
Reliability	The ability of the lab to perform its required functions under specified conditions and for a specified time.
User management	The user management describe how the users get access to the online labs, how their data is managed, what user rights they have, and the storage of their experiment data set.
Management of usernames and password	Management of usernames and password describes the controlled mechanism to provide legible and secure access to the online lab.
User's authentication	Describes the authentication mechanism for the user.
Maintain authentication and access right	Describes the management of the authentication mechanism.
Personal learning environment	Personal learning environment, describes the facilitation of an individualized and informal learning environment.
Personal dashboard and record store	The degree to which the learning environment is individualized and informal.
Queue & booking management	Queue & booking management or scheduling system describes the application that can be used to reserve lab resources for a limited time without conflict, thus preventing parallel use.
Accessibility & availability	The extent to which the availability and efficiency of the lab is limited.
Accounting	The integration of an accounting system with the booking management.
Safety and security	Safety and security must be provided for the user and the operator as well as for the security of the system itself and its data.
Security (client & server)	The level of security on the client and server side.
Safety (people)	The degree of operational safety of labs for people, equipment and the environment.
Scalability and extensibility	Describes how easy it is to adapt the labs to new target audiences, extend them with more experiments, scale them to more facilities, certify the results, and ensure sustainability.
Audience	Audience describes the characteristic addressed by the online lab, which demands, problems or needs the target group should have.
Information about lab	Describes how well the information about the characteristics of the labs is available to further specify the audience.
Diversity of audience	Describes how diverse the audience is addressed (user groups, field of industry, level of education).
Extensibility	Extensibility describes the ability of an online lab to be used beyond its original utility through adaptability, heterogeneity & interchangeability, and interoperability, which should enable a kind of plug-and-play paradigm.
Adaptability & interoperability	Describes the ability of the lab architecture to easily connect components while still having a design that is specific to the target audience.
Scalability	Scalability describes the ease with which copies can be made in terms of the number of users as well as the number of experiments to serve a potentially unlimited number of users and online labs.
Scalability	Describes the technical scalability of the lab in terms of the number of users and experiments.
Shareability	Describes the organizational ability to scale across its own unit.
Certification	Certifications describe on the one hand the validation of the learning content by third parties and on the other hand address the needs of the people who need a qualification certificate.
Certified (learning) material	Describes the extent of the certified (learning) material.
Certified (learning) achievements	Describes the extent of the certified (learning) achievements.
Price and sustainability	Price and sustainability describes the ability of online labs to exist continuously and across product cycles, describing a fundamental need for scalability and extensibility.
Cost & revenue	The allocation of costs and revenues with the goal of a sustainable business model.
Learning support	Whether and to what extent the online lab supports coursework, while also supporting social coordination, the lab environment, and individual differences.
Learning environment	Learning environment describes the cognitive, affective, and psychomotor services that can be achieved in a lab.
Type of experiment	Describes the extent to which the nature of the labs allows the parameters and environment to be changed remotely.
Reconfigurability	Describes how easily the learning environment can be modified, redesigned, and adapted to new processes.

Pedagogical framework	Describes available frameworks and procedures for teaching and assessing learning in the lab.
Interactivity and realism	Interactivity and realism mean that the environment must engage the interest and motivation of the students.
Authenticity	Describes genuineness in the sense of originality.
Interactivity	It describes working together, with this promoting both motivation and cognitive engagement.
Technical support and maintenance	Describes the extent to which the operator has response capabilities in the event of a failure of individual components or the entire lab.
Technical documentation	Describes the presence of technical documentation of all technical lab components and their interaction.
Supportive staff	Describes the availability of qualified personnel for secure operation.
System monitoring	Describes the degree to which a real-time monitoring system provides continuously updated system information.
Didactic support	Describes the didactic use of the lab, the resources available, and whether the lab facilitates the work of students and teachers.
E-learning material	Describes the availability and diversity of self-explanatory e-learning materials.
Interaction support	Describes the extent to which student-faculty and student-student interaction is supported by the lab.
Learning platform	Describes the extent to which the lab supports learning progress in a learning platform.

Appendix D: Expert Case Studies of Maturity Model

Maturity dimensions	Expert workshop						Expert Interview						
	Real Lab 1	Lab Sim 1	Real Lab 2	VR/AR Lab 1	VR/AR Lab 2	VR/AR Lab 3	Real Lab 3	Real Lab 4	Lab Sim 2	Real Lab 5	Lab Sim 3	µ	SD
Universality and accessibility	3,4	3,8	2,3	2,2	2,3	2,3	3,9	4,4	3,8	4	3,8	3,3	0,84
Universality and accessibility	4	4	1	1	1	1	5	5	4	5	5	3,3	1,85
Multi-platform client	4	4	1	1	1	1	5	5	4	5	5	3,3	1,85
Installation	3,5	5	3	5	4	4	4,5	5	5	5	4	4,4	0,71
Installation and use	4	5	3	5	4	4	5	5	5	5	5	4,5	0,69
Integration	3	5	3	5	4	4	4	5	5	5	3	4,2	0,87
Interface	2,5	1,5	3	2,5	4	4	2,5	3,5	3,5	3,5	4	3,1	0,81
Real looking GUI	3	1	4	4	5	5	3	4	3	4	3	3,5	1,13
Interface adaptability	2	2	2	1	3	3	2	3	4	3	5	2,7	1,10
Efficiency	4,0	4,7	2,3	1,7	1,3	1,3	4,7	4,3	4,3	5,0	3,7	3,4	1,44
Required client hardware	5	5	3	2	2	2	5	5	5	5	5	4,0	1,41
Network resources	3	4	3	1	1	1	4	5	4	5	3	3,1	1,51
Technical support and maintenance at lab side	4	5	1	2	1	1	5	3	4	5	3	3,1	1,64
Trustability	3,0	3,7	2,3	1	1	1	2,7	4,3	2,3	1,7	2,3	2,3	1,10
Relationship stage	5	5	3	1	1	1	4	3	2	1	1	2,5	1,63
Social features	2	4	2	1	1	1	1	5	2	1	3	2,1	1,38
Reliability	2	2	2	1	1	1	3	5	3	3	3	2,4	1,21
User management	3,1	3,5	2,1	2,8	2,8	2,8	3,9	4,5	3,5	3,6	3,6	3,3	0,66
Management of usernames and password	4	3	2	3	3	3	5	5	5	4,5	4	3,8	1,03
User's authentication	4	3	1	3	3	3	5	5	5	5	3	3,6	1,29
Maintain authentication and access right	4	3	3	3	3	3	5	5	5	4	5	3,9	0,94
Personal learning environment	3	4	1	3	4	4	2	3	2	3	5	3,1	1,14
Personal dashboard and record store	3	4	1	3	4	4	2	3	2	3	5	3,1	1,14
Queue & booking management	2	2,5	2	2	1,5	1,5	4,5	5	3	3	2,5	2,7	1,15
Accessibility & availability	2	3	3	N/A	2	2	4	5	4	5	4	3,4	1,17
Accounting	2	2	1	2	1	1	5	5	2	1	1	2,1	1,51
Safety and Security	3,5	4,5	3,5	3	2,5	2,5	4	5	4	4	3	3,6	0,80
Security (client & server)	3	4	3	3	4	4	4	5	4	5	3	3,8	0,75
Safety (people)	4	5	4	3	1	1	N/A	5	4	3	3	3,3	1,42
Scalability and extensibility	2,6	3	2,7	2	1,4	1,6	3,4	3,4	3,1	3,1	3,4	2,7	0,73
Audience	3	4	3,5	3	3	3	3	5	4	3	4,5	3,5	0,72
Information about lab	3	4	4	3	3	3	3	5	3	4	5	3,6	0,81
Diversity of audience	3	4	3	3	3	3	3	5	5	2	4	3,5	0,93
Extensibility	3	3	3	1	1	1	3	5	3	3	5	2,8	1,40
Adaptability & interoperability	3	3	3	1	1	1	3	5	3	3	5	2,8	1,40
Scalability	3	4,5	3	4	1	2	4,5	4	4	4,5	2	3,3	1,21
Scalability	3	4	3	3	1	1	4	5	4	5	3	3,3	1,35
Shareability	3	5	3	5	1	3	5	3	4	4	1	3,4	1,43
Certification	3	2,5	3	1	1	1	2,5	2	2,5	2	2	2,0	0,76
Certified (learning) material	3	2	3	1	1	1	4	2	2	2	2	2,1	0,94
Certified (learning) achievements	3	3	3	1	1	1	1	2	3	2	2	2,0	0,89
Price and sustainability	1	1	1	1	1	1	4	1	2	N/A	N/A	1,4	1,01
Cost & revenue	1	1	1	1	1	1	4	1	2	N/A	N/A	1,4	1,01
Learning support	3,2	4	3,8	3,7	3,5	3,2	2,7	4	4	3,7	3,8	3,5	0,39
Learning environment	3	4	3,3	3,3	4	2	3	5	4	4,3	4	3,7	0,85
Type of experiment	4	5	4	5	5	3	5	5	5	5	5	4,6	0,67
Reconfigurability	2	3	3	1	3	1	3	5	5	3	5	3,1	1,45
Pedagogical framework	3	4	3	4	N/A	N/A	1	5	3	5	3	3,4	1,24
Interactivity and realism	3	4,5	4	4	4	4	2	4	3,5	3	4	3,6	0,71
Authenticity	3	4	3	4	4	4	3	3	3	3	5	3,5	0,69
Interactivity	3	5	5	4	4	4	1	5	4	3	3	3,7	1,19
Technical support and maintenance	3	3,7	3,7	3,0	2,3	3	3,7	3,7	3,3	4,3	3,7	3,4	0,53
Technical documentation	3	3	3	2	2	2	3	4	4	5	3	3,1	0,94
Supportive staff	3	5	5	5	3	5	4	4	3	5	5	4,3	0,90
System monitoring	3	3	3	2	2	2	4	3	3	3	3	2,8	0,60
Didactic support	3,7	3,7	4,0	4,3	3,7	3,7	2,0	3,0	3,7	3,0	3,0	3,4	0,63
E-learning material	4	4	5	5	5	5	1	3	4	3	5	4,0	1,26
Interaction support	4	4	4	3	3	3	4	1	3	1	3	3,0	1,10
Learning platform	3	3	3	5	3	3	1	5	4	5	1	3,3	1,42

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