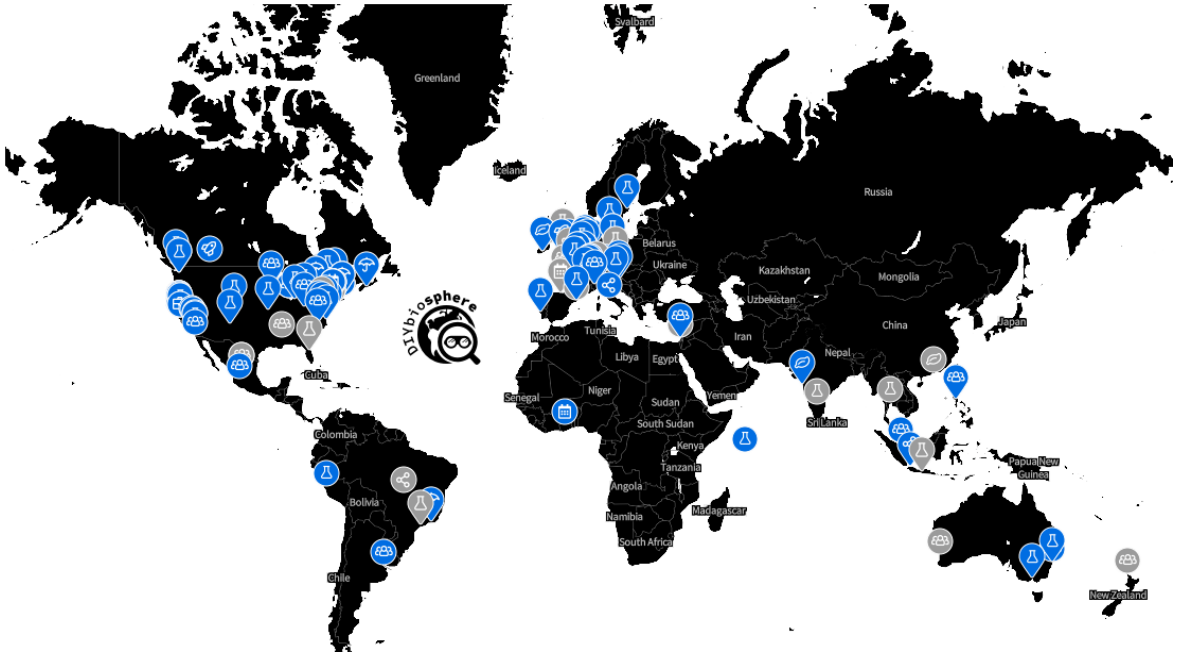
Master Thesis – master Innovation Sciences

Self-made success, achieved together

How and why the DIYbio community engages in DIYbio projects and what makes them successful.



Source: Screen capture from DIYbiosphere, accessed through https://sphere.diybio.org/

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Abstract

In order to solve complex sociotechnical challenges scientific research is moving to a more democratized and socially distributed state. Synthetic biology is one of the fields in which one such movements has started, called the Do-It-Yourself-Biology (DIYbio) community. Cheaper equipment, communication technologies and automation of DNA sequencing and -synthesis increasingly allow DIYbiologists to start experimenting in self-made labs. The DIYbio community can be classified as a user community engaging in open, collaborative innovation projects, but it is unclear what makes these projects successful. This research therefore first investigates how and why the community members engage in DIYbio projects and then what characteristics make projects successful. User innovation and user community literature is used, along with literature on project success. Six characteristics are hypothesized to influence DIYbio project success: regulation, technology and market as industry specific factors and leadership, knowledge diversity and funding as project specific factors. To find out the motivations of DIYbiologists, 9 interviews with community, project, startup and lab leaders from over the world were conducted, transcribed, coded and analyzed. To find out what makes DIYbio projects successful, a survey was conducted among the DIYbio community with a response of 32. Ordinary Least Squares regression was performed in *R* to uncover possible relationships between the six independent variables and project success, supported by qualitative data of the interviews. Differences in how and why DIYbio is done are found between the US, EU and countries in Africa, South-America and Asia and between technology-oriented people and bio artists. The groups are connected through dissatisfaction with their jobs, a degree of activism, the urge to seek like-minded people, experimenting in their free time and an entrepreneurial mindset. A DIYbio project cycle from new to successful projects in relation to regulation, technology and market is created and key activities to enable DIYbio project success are defined based on interview data. In the regression analysis, the variable knowledge diversity is proven to have a positive significant relationship with project success. The different identified groups in the DIYbio community have different relationships to the six project characteristics because of their different motivations and cultures. The six project characteristics all have an influence on project success, but the exact relationships are more complex than a positive linear relation. The results are reflected on and compared to user community literature based on Open Source Software which unveils differences between the two communities.

Contents

1. Introduction

Modern societal problems such as public health are complex, interconnected and urgent, requiring insights from more perspectives than scientific knowledge and technological innovation in order to be solved (Ferretti & Pereira, 2021; Frow et al., 2015; Mazzucato, 2018). Scientific research is therefore moving towards a more socially distributed and democratized state where everyone in society is able to contribute (Ferretti & Pereira, 2021; Jackson et al., 2019; Yoon et al., 2020). The urge to contribute to solving societal problems has sparked a movement in scientific fields, challenging the notion that scientific knowledge production is almost exclusively performed by universities and research institutes (Fox, 2014; Sarpong et al., 2020).

The collective name for the community-based independent scientific research movement is called Do-It-Yourself(DIY)-science (Fox, 2014). DIY started with making simple everyday life items such as chicken coops (subsistence DIY). Then, firms started producing pre-made kits which people bought to make something themselves (industrial DIY). The third wave of DIY (new DIY) is now emerging. Characterized by relatively cheap laboratory equipment and advancements in communication and other web-based technologies, people can invent, design and make basically everything themselves. (Fox, 2014) DIY science allows a democratization of science as private homes and community spaces become sites for experimentation, education and eventually for successful (commercial) products (Meyer, 2013).

One of the scientific fields in which the movement from rigid and institutionalized to a more distributed and democratized way of scientific research is taking place is synthetic and molecular biology (Landrain et al., 2013; Sarpong et al., 2020). This movement is called Do-It-Yourself biology or DIYbio (Delgado, 2013). On top of cheaper equipment and communication technologies, the increasing productivity because of automation of DNA sequencing and -synthesis is especially crucial for the rapid growth of this community (Delgado, 2013; Ledford, 2010). The areas in which synthetic biology research has the most potential to contribute to solving societal challenges are agriculture, manufacturing and medicine (Kelley et al., 2014; Voigt, 2020). These potential applications have created tremendous ‘hype’ and hope for DIYbio, but at the same time raise questions concerning biosafety, biosecurity and bioterrorism (Ledford, 2010; Sarpong et al., 2020; Seyfried et al., 2014).

The DIYbio movement is a growing global community of biologists focused on promoting and performing democratized and bottom-up innovation, presenting a case of user innovation (Delgado, 2013; Landrain et al., 2013; Seyfried et al., 2014; von Hippel, 2009). User innovation literature often focuses on the innovation process around a specific technology (Demonaco et al., 2020; Franke & Shah, 2003; Riggs & von Hippel, 1994; von Hippel, 2009) or the characteristics of a single user entrepreneur (Habicht et al., 2012; Morrison et al., 2000; von Hippel, 1976, 1989). DIYbio is not bound to a single technology and is a community rather than single user entrepreneurs, it is more specifically a case of a user community performing open, collaborative innovation (Baldwin & von Hippel, 2011).

Previous literature on user communities is often based on either (extreme) sports or open source software projects (Dahlander & Frederiksen, 2012; Esposito De Falco et al., 2017; Hienerth, 2006). Previous literature on DIYbio tends to focus on the technological promises and challenges (Awad et al., 2018; Landrain et al., 2013; Ledford, 2010; Sarpong et al., 2020; Seyfried et al., 2014), characteristics of user entrepreneurs (You et al., 2021) or quality and safety concerns (Ferretti & Pereira, 2021; Yoon et al., 2020).

The first aim of this research was to find out how and why the DIYbio community engages in

open, collaborative innovation projects. To do so, the similarities and differences in motivations to engage in DIYbio were identified. The different motivations of people in the community lead to different types of DIYbio projects. It would be interesting to find out whether there are certain aspects of a DIYbio project that increase its chance of succeeding. Therefore, the second aim of this research was to investigate which project characteristics influence the success of DIYbio projects. This leads to the following research questions:

RQ1: What is the influence of the DIYbio community on DIYbio project characteristics?

RQ2: Which project characteristics determine the success of DIYbio projects?

Answering these questions contributes to literature in several ways. First of all, user innovation/community studies often take into account one specific technology or the characteristics of a user-entrepreneur. The project level allows multiple technologies to be taken into account, as well as the characteristics of different groups in a community. Also, the empirical data in user communities literature is often based on (extreme) sports or open source software (OSS). It is therefore interesting to test the theoretical concepts derived from these cases on the DIYbio community. Gaining a deeper understanding of the project success of DIYbio projects and the effect of the DIYbio community also helps in a societal context, because it is unclear when projects are successful and how different successful projects add value to society.

2. Theory

This chapter first presents the theoretical foundations of user innovation, user communities and open collaborative innovation projects on which this research is based. Next, variables are defined and hypotheses are formulated. Finally, all the theoretical concepts are combined in a conceptual model.

2.1 User innovation, user communities & open collaborative innovation projects

Users can play a major, sometimes even dominant role in the innovation process of an industry (Gambardella et al., 2017; Riggs & von Hippel, 1994; von Hippel, 1976). In user innovation in manufacturing industries, users invent, prototype and field-test products while the role of a commercial manufacturer is to perfect the prototype and to produce it on a large scale (von Hippel, 1976). Innovations with high scientific importance are often developed by users while innovations with high commercial importance are often developed by manufacturers (Riggs & von Hippel, 1994). User innovation complements manufacturer innovation because of different incentives, different knowledge and capabilities and free revealing (Henkel & Hippel, 2004).

Industries have become more complex over the years because of automation and information technologies (Jasperneite et al., 2020). It is this complexity and heavy reliance on scientific knowledge that motivates DIY biologists to start experimenting (Sarpong et al., 2020). A special group of users are the so-called 'lead users' who experience needs before others and benefit from obtaining a solution for these needs (von Hippel, 1989). Previous research on the characteristics of lead users shows that lead users often have a leader status within a user group, possess technical capabilities and openly share information (Morrison et al., 2000). While user innovators or lead users can be regarded as (and sometimes are) isolated and individual innovators, they often need information and assistance in various ways to innovate (Franke & Shah, 2003). This is why user innovators can also be part of a user community of people who share the same interests and collaborate voluntarily (Franke & Shah, 2003).

Many societal problems no longer require just technical solutions but also have a social component (Ferretti & Pereira, 2021). The sociotechnical nature of problems causes a complexity which requires collaboration to solve them, causing a shift from a closed to an open innovation paradigm (Chesbrough, 2003). While the research and development activities of firms are often based on a proprietary model where exclusive property rights and managerial control are central, community-based models rely on neither exclusive property rights nor managerial control (DiBona et al., 2005). An important aspect of the user community mindset is free revealing, as users often openly share information about novel products or services so others may use them, learn from them and perhaps improve them (Von Hippel & Von Krogh, 2006). It is often hard to protect this information anyway and the revealer may profit from it in other ways, e.g. network effects or becoming the dominant design (Von Hippel & Von Krogh, 2006). Baldwin & von Hippel (2011) therefore propose three distinct innovation models: open collaborative innovation projects, typical single user innovations and producer innovations. The defining properties of open collaborative innovation projects are that the participants are not rivals with respect to the design and they do not plan to sell products or services that they create (Baldwin & von Hippel, 2011). These defining properties correspond to the ideals of the DIYbio community.

The DIYbio statement of shared purpose is to: *"Fundamentally transform life sciences and democratize biotechnology to inspire creativity and improve lives by organizing life science change-makers and bioenthusiasts to build an inclusive global network, cultivate an accessible commons of knowledge and resources, launch community labs and projects and enable local educators"* (Global Community Biosummit, 2020). The statement shows the

community-based model instead of the proprietary model that is often used by the traditional pharmaceutical industry (Munos & Chin, 2011). The community also shows the open innovation/free revealing mindset and aims to fulfill unmet needs experienced by the members. The community members do not see each other as competitors or rivals and the goals of projects go beyond commercial interests, making DIYbio a user community with open collaborative innovation projects (Baldwin & von Hippel, 2011).

Determining the success of projects remains a challenge, since critical success factors are hard to generalize and objectively assess (Bergmann & Karwowski, 2019; Shenhar et al., 2002). Success factors can differ based on uncertainty and scope of projects, as well as between sectors (Baccarini & Collins, 2003; Shenhar et al., 2002). According to a literature study conducted by Moradi et al. (2020), the great variety in projects and sectors has led to 65 possible success factors (Moradi et al., 2020). Since measuring all the factors for every project costs a lot of time and resources, certain factors are often chosen based on the sector and project type (Adabre & Chan, 2019; Moradi et al., 2020). Hence, defining success in DIYbio is done in section 2.2 and factors which possibly influence the success of DIYbio projects are explained in section 2.3.

2.2 Dependent variable: Project success

The creation of a new product in the pipeline of the pharmaceutical and biotechnology industry can be divided in three distinct phases: discovery, development and commercialization (Rang & Hill, 2013). The products developed in DIYbio projects mainly consist of pharmaceutical and biotechnological products (DIYbiosphere, n.d.). In DIYbio projects, commercialization is not the only outcome. The product can also be diffused in different ways, for example through free revealing. Hence, DIYbio projects can be divided in three phases: discovery, development and diffusion.

No matter which phase a project is in, it is important that the project reaches the goals that are set to be achieved and is therefore successful. The goals of DIYbio are to experiment, educate and launch community labs and projects (Global Community Biosummit, 2020). Experimentation and education are important conditions to enable the success of community labs and projects. From a perspective of developing a product to the extent that people can use it, the success of a project can be seen as having a proof of concept or a working product, and it would be ideal if the product would also reach as many people as possible. Developing products in biotechnology is paired with a high rate of failure (Casper, 2000), so the outcome is not the only useful aspect of a research project. Success can also be reached in the process when a project is performed in a satisfactory manner (de Wit, 1988). This is especially true for DIYbio, where experimentation without outcome and learning new skills is highly encouraged (DIYbio community, n.d.) The dependent variable of this research therefore is project success, in which a project is delineated to the discovery, development and diffusion of one product innovation and success is based on both outcomes and process.

2.3 Independent variables

While success is judged based on the outcomes and process, every project has specific factors that influence both the outcomes and the process (Lim & Mohamed, 1999). For the projects studied in this research, the influencing factors are divided into project characteristics and project conditions. Project characteristics are the features that are most influential for biotechnology projects while project conditions refer to the set-up of the projects.

2.3.1 Project characteristics

Regulation

The first characteristic of biotechnology projects is that projects are influenced by many regulations. Since healthcare deals with the preservation and quality of life and is technologically complex, many societies have decided that healthcare should be of 'high' quality and widely available (Weisbrod, 1991). The wish to provide high quality care has caused the healthcare sector to be highly regulated by both governmental and private organizations (Lakomaa & Sanandaji, 2021). On the one hand high regulation can cause obstacles for the innovation process because experimentation can be limited. DIYbio projects must also comply with existing regulations if they want to stimulate the diffusion of a successful project outcome, exemplified in the community-created biological safety handbook (Armendariz et al., n.d.). On the other hand, regulation can create new opportunities and force out-of-the-box thinking. For DIYbio projects, the interplay between regulation and innovation can also cause both opportunities and barriers. Opportunities are created because highly regulated technologies might not be worth experimenting with for large biotechnology firms, and therefore leave room for DIY biologists, especially if they identify an unmet need that can be addressed using this technology. An example of an opportunity is the ability of the Real Vegan Cheese project to produce genetically engineered bacteria because regulation was already in place but no biotechnology firms were interested in producing cheese using this technology (Real Vegan Cheese, n.d.). So while regulations can provide opportunities, the end goal of a successful product goes hand in hand with compliance to regulation. The first independent variable therefore is the degree to which regulation forms a barrier, with both too much and too little regulation having a negative impact on project success. This results in Hypothesis 1:

H1: A moderate level of regulation leads to an increase in project success.

Technology

A second factor which influences project success is the constantly expanding technological frontier (Thierer, 2020). While the regulatory environment contributes to the safety and quality of products and services for users, it also limits both entrepreneurship and innovative capabilities (Herzlinger, 2006; Phillips & Garman, 2006). Experimentation with new technologies is limited because it is paired with uncertainty of the risks of the new technology or ethical concerns (Thierer, 2020). Users, DIYbio labs in particular, are perfect to fulfill this need and experiment with new technologies because they are able to circumvent regulations in experimentation and can be 'evasive entrepreneurs' (Thierer, 2020). The accelerating pace of democratization of biotechnology research methods allows new technologies to become available quicker for people with a lower amount of skills and resources (Jackson et al., 2019). Where technologies such as DNA sequencing took over a decade to become available to hobbyists, cutting edge technologies like CRISPR[1] genome editing only took four years (Jackson et al., 2019). The quicker availability of technologies, combined with uncertainty and risks leads to the expectation that DIYbiologists experimenting with more novel technologies have more successful projects. The second independent variable therefore is the technological novelty of the technology used in the project. This results in Hypothesis 2:

H2: Experimenting with a novel technology leads to an increase in project success.

Market

The third factor of project success in biotechnology is the potential market for the product. The market, and therefore potential revenue, is dependent on the number of people with a certain condition and the nature of both the condition and the treatment. Firms are often incentivized by large markets because they can ensure that they earn back their extensive investments.

1 CRISPR is an abbreviation for Clustered regularly interspaced short palindromic repeats

However, the small markets of rare diseases with a one-time treatment are also interesting because of subsidies, special exemptions and other regulations (Simoens et al., 2012). For the smallest markets of ultra-rare diseases where development- and collaboration costs outweigh the advantages there is no incentive for firms, single users and user communities, but rather for non-profit foundations (Baldwin & von Hippel, 2011; Crooke, 2022). A moderate market size occurs when the market size is too large to be treated as a rare disease, but not big enough for pharmaceutical firms to be incentivized to develop a product. Therefore user innovation is most likely to occur with a moderate market size (Lakomaa & Sanandaji, 2021). These markets leave a gap for DIYbio projects to identify unmet needs and develop a product. The third independent variable therefore is market size, with both a large and small market having a negative impact on project success. This leads to Hypothesis 3:

H3: A moderate market size leads to an increase in project success.

2.3.2 Project conditions

Leadership

In development projects in biotechnology companies, interpersonal skills of the project leader are important for the success of a project (Salgado et al., 2017). Previous literature on user communities, specifically in OSS, also shows that leadership is an important factor in success (Lerner & Tirole, 2002). Leaders in projects need cognitive, structural and processual leadership skills, connecting the different personalities and backgrounds of project participants and promoting constructive interactions (Gray, 2008). The interesting contrast with DIYbio is that the whole community is focused on being democratic and inclusive. Because of this, there are seemingly no formal leaders in the global community and the smaller communities and labs (DIYbio community, n.d.). This is similar to OSS communities, where there is no formal leader, but programmers who are looked up to have 'real authority' instead of 'formal authority', meaning their vision is still largely followed (Lerner & Tirole, 2002). It is therefore interesting to find out whether the projects performed by the community do have a competent leader and what kind of authority they have. The fourth independent variable therefore is the presence of a competent project leader. This leads to Hypothesis 4:

H4: The presence of a competent project leader leads to an increase in project success.

Knowledge diversity

On top of having a clear project leader, having access to skills and knowledge from multiple disciplines in the project team is important (Salgado et al., 2017). In the last decades, transdisciplinary research projects have gained momentum because they offer an integrative approach that transcends a single research discipline, which is necessary for complex societal problems (Rosenfield, 1992). It is hard for people to engage in transdisciplinary research projects because of differences between disciplines in methodologies and mentalities (Ramadier, 2004). This also applies to small biotechnology firms, and even for large firms to set up these kinds of research projects.

A unique aspect of the DIYbio community is that people already have different backgrounds when engaging with others in the community, and from this point the project is built up. On top of that, community members are constantly trying to teach themselves and others new techniques and are open to insights from different backgrounds. An example is the Open Insulin project in which biological engineers and chemists collaborate with people with experience with pharmaceutical regulation, diabetes patients and even high school students with different backgrounds (*Open Insulin Project*, n.d.). The fifth independent variable therefore is the variety of technical skills in the project, leading to Hypothesis 5:

H5: A high degree of variety in knowledge and skills leads to an increase in project success.

Funding
Despite costs of equipment and raw materials going down rapidly (Delgado, 2013; Ledford, 2010), research and development in the biotechnology sector is not a cheap venture. Funding is therefore one of the critical success factors of biotechnology startups (Vanderbyl & Kobelak, 2007). Usually, startups are dependent on venture capitalists for their early funding. Venture capitalists require a clear business plan, managers with a track record and an exit strategy (Vanderbyl & Kobelak, 2007). Also, biotechnology is a diverse field causing investors to not always fully understand the technology they are investing in (Vanderbyl & Kobelak, 2007). Both a lab to experiment in and specific funding for projects seems to be needed. The sixth independent variable therefore is the amount of funding.

H6: An increase in funding leads to an increase in project success.

2.4 Conceptual model

The variables and their relationships are displayed in the conceptual model below, *Figure 1*. The variables 'degree of regulation' and 'market size' are expected to have an inverted U-shape relation with project success, meaning that low and high scores are expected to lead to a decrease in project success and a moderate score to lead to an increase in project success. The rest of the independent variables are expected to have a positive linear relationship with project success, meaning that an increase in the independent variable leads to an increase in project success.

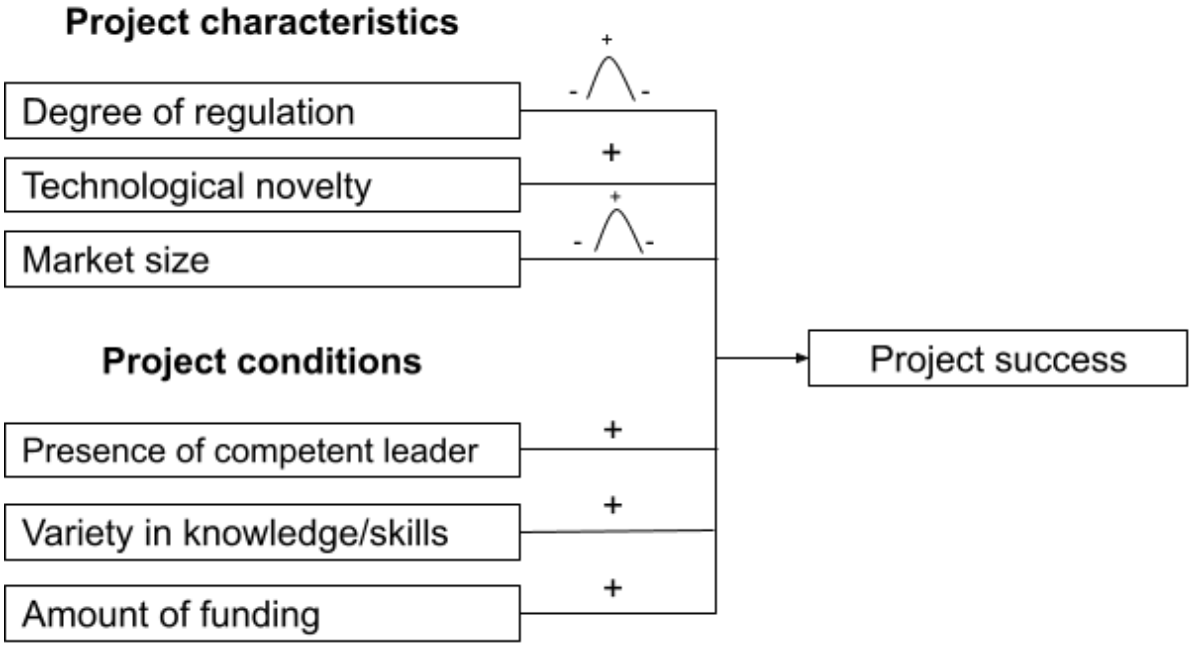

Figure 1. Conceptual model.

3. Methods

In this chapter, the general research design is first outlined and justified. Then, data collection and sampling for both the quantitative and qualitative research strategies is explained. Finally, variables are operationalized and the strategy for data analysis is presented.

3.1 Research design

Primary data collection was used because there was no readily available data about DIYbio projects. Due to the primary data collection strategy and the fact that research on DIYbio is relatively new, the nature of this research was exploratory. Previous studies on the DIYbio community focused on how the DIYbio community was formed and what drives DIY biologists. However, these studies are all based on 1 to 5 case studies, focusing on the biggest success stories and/or the pioneers (Delgado, 2013; Landrain et al., 2013; Sarpong et al., 2020; Seyfried et al., 2014). The aim of this research is to how the DIYbio community influences DIY project characteristics and whether certain project characteristics influence project success. In order to uncover the relationships which were expected based on theory, both qualitative and quantitative research methods were employed. The qualitative data is useful for detailed insights in the DIYbio community and its influence on projects and project characteristics, and is therefore useful to answer research question 1. The qualitative data was obtained from a series of semi-structured interviews with DIY biologists, which were coded and analyzed to obtain a narrative about the DIYbio community and projects. The quantitative data is useful for objective analysis of the proposed relationships based on theory and is therefore useful to answer research question 2. The quantitative data was obtained by conducting a survey among DIY biologists, which was used for regression analyses to uncover relationships between projects characteristics and success. The qualitative data was used to give context to the outcomes of the quantitative data in answering research question 2. The research strategy of this research is both deductive for the quantitative regression analysis and inductive for the qualitative narrative analysis. The different methods used in this research are displayed below in *Figure 2*.

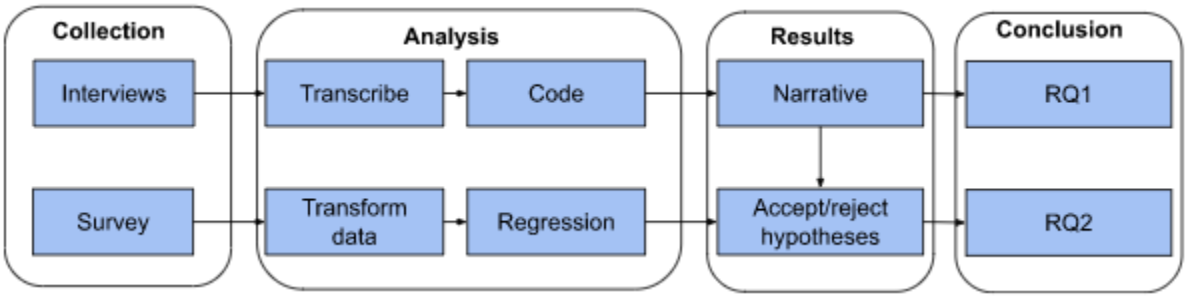

Figure 2. Outline of the research design.

3.2 Sampling and data collection

3.2.1 Qualitative data sampling and collection

The sampling strategy of this research consisted of both purposive and snowball sampling (Bryman, 2016). First, purposive sampling was to identify community leaders in the DIYbio community. After contacting five informal leaders from the Global Community Biosummit 5.0, one responded and agreed to an interview. Simultaneously, the survey was spread and the first survey respondents were contacted for interviews to which two people responded. From here, snowball sampling was used to identify the rest of the interviewees who could give unique perspectives (Noy, 2008). Interviews were conducted online through Zoom, Google

Meet and MS Teams because all interviewees lived outside of the Netherlands. 9 interviews were conducted which yielded different perspectives within the DIYbio community. Theoretical saturation was almost reached because the last interviews contained a lot of repetition of what earlier interviewees said. Within the given time-frame of this research, this was satisfactory and also matched the expectations based on Guest et al. (2006) who indicated that saturation is often reached between 6 and 12 interviews (Guest et al., 2006). The interviews were semi-structured and built on the assumption that interviewees had already filled in the survey. The interview guide can be found in *Appendix A*.

3.2.2 Quantitative data sampling and collection

A list of community biology projects was found at www.DIYbio.org, the website of the DIYbio community. This is a collection of projects, startups and labs, both active and inactive. However, this list is incomplete and outdated, as there are numerous labs, projects and startups which can be seen at a first glance at the community but which are not included in this list. Since there was no available DIYbio project data of the variables used in this research, primary data collection was required. The quantitative data collection strategies consisted of three steps. First, the online survey was spread through the communication channels used by the DIYbio community, which were Slack, Facebook and Google Groups. In order to gain legitimacy within the community, one of the community leaders gave permission to use their name in the message that was spread. The second step was to contact labs and startups who were represented at the latest Global Community Biosummit 5.0 which took place from the 19th until the 21st of November 2021. The biosummit is the largest (online) global gathering of the DIYbio community. At this conference, a list with participants was shared with all attendees. This list of initiatives formed the starting point of the sample, since this is the most comprehensive and up-to-date overview of the DIYbio community. A total of 100 labs, individuals and startups were contacted through email, LinkedIn and contact forms and the survey was spread on separate Facebook, Reddit, Slack groups and privately run forums; a list can be found in *Appendix B*. Additionally, a database of iGEM projects was found and used (*IGEM Video Universe*, n.d.). iGEM is an international synthetic biology competition for high schools and universities. While this was originally considered to be outside the scope of this research, a combination of making the inclusion criteria more flexible due to feedback of interviewees and an initial low survey response led to the inclusion of these projects. A total of 527 iGEM projects were based around the tracks ‘Health and Medicine’ (before 2015) and ‘Therapeutics’ and ‘Diagnostics’ (after 2015). Using the website Apify (www.apify.com), a web scraper was used to obtain email addresses of these projects since there were no contact details provided in the database (*Web Scraper · Apify*, n.d.). This resulted in 561 unique email addresses to which an email with an invitation to fill in the survey was sent. The final step consisted of snowball sampling from the initial survey respondents and interviewees, since the community turned out to consist mostly of overlapping personal networks.

The questions for the survey can be found in *Appendix C*. The questions where respondents have to quantify or indicate a category are the main questions for the quantitative part of this research. However, for each question there is room for elaboration on how the respondent got to this answer. The survey was made using the programme Qualtrics using the Utrecht University license.

3.3 Operationalization of variables

In this section, the variables identified in the theory chapter are operationalized for the quantitative part of this research.

3.3.1 Project success

With the multitude of objectives on technological and social levels, it is near impossible to objectively measure the success of a project (de Wit, 1988). There are no readily available indicators for the success of projects, especially for DIYbio projects. Therefore, the success of projects will be determined directly by the survey participants. The most appropriate criterion for measuring the success of goals is to see to what degree the project goals have been reached (de Wit, 1988). Success is not only determined by the outcomes but can also be reached by being satisfied by the process (Lim & Mohamed, 1999). The project success will therefore be measured by two indicators: effectiveness and satisfaction. Effectiveness entails whether the goals set out for the project have been reached and will be asked on a scale from 0% to 100%. Satisfaction is the extent to which the respondents are satisfied with both the outcomes and the process of the project. These will also be scored on a scale of 0% to 100%. The total score for the project success score is calculated as follows:

$$\frac{Effectivenessscore + \left(\frac{Satisfactionscoreoutcome + Satisfactionscoreprocess}{2}\right)}{2}$$

3.3.2 Project characteristics

Degree of regulation

The degree of regulation perceived as a barrier will be measured by using the notion of regulatory density as proposed in Klein et al. (2021). Regulatory density is the relative amount of standards and procedures that need to be adhered in order to develop a product (Klein et al., 2021). The perceived regulatory density will be compared to the perceived risks and uncertainty around the product that is developed in the project. The difference between these measures will indicate whether regulations are perceived as a barrier and is called the 'degree of regulation'. Both regulatory density and uncertainty will be asked on a scale of 0 to 100 and transformed to a value between 0 and 1. The score for uncertainty and risks will then be subtracted from the score for regulatory density. The result is a value between -1 and 1, where -1 means that there are no regulations for a complex product associated with uncertainty and risks and 1 means an excess of standards and procedures for a low uncertainty product. *Table 1* shows an overview of the categories associated with scores:

Table 1. Degree of regulation and interpretations

Regulatory density score minus uncertainty score	**Interpretation**
-0,05 to 0,05	Perfect regulatory equilibrium
0,05 to 0,1 and -0,05 to -0,1	Regulatory equilibrium
> 0,1	Regulation is a barrier
< -0,1	Existing regulation is not sufficient

Technological novelty

Since the goal is to determine the novelty of the technology used in the project, a way of measuring technological maturity of a technology is needed. A systemic measure for technological maturity is the Technological Readiness Level (TRL) (Mankins, 1995). The TRL scale consists of 9 levels which range from observing the basic principles to having a proven working system in an operational environment (Héder, 2017). TRL originally started as a

measure for space programs but has since become a widely used measure in innovation policy (Héder, 2017). The TRL scale will be used to determine the technological novelty of the technology used, where a lower level corresponds to a more novel technology. The full scale can be found in *Appendix D*. Since the interest is in the novelty of the technology used, the exact level of TRL does not matter. The answers are therefore transformed to a binary variable, where 0 means TRL 4 or lower and 1 is TRL 5 or higher. The distinction is made here because having a proof of concept (TRL3) and a functional verification (TRL4) are still signs of a technology being in its early stages.

Market size

The market size will be measured by asking respondents to identify the market which they plan on seizing with the product which is developed in the project. The method will be similar to Lüthje et al. (2005) in which respondents are asked to identify where their product is in the development process. Instead of the categories of development process used in Lüthje et al., 2005, the categories of this indicator will be based on the intended market size. The categories are displayed in *Table 2*:

Table 2. Operationalization of market size variable

Category	Intended market size
1	Individual or project team use
2	Local or DIYbio community
3	National market
4	Global market

3.3.3 Project conditions

Presence of leader

For this research, it is interesting to find whether there is a clear leader of the project with decision-making authority. The respondents will be asked to choose the most appropriate option of decision-making authority for their project. Since the expectation is that having a single competent leader has a positive effect on project success, it is compared to other modes of leadership. Table 3 shows the categories from which the respondents can choose.

Table 3. Categories of decision-making authority

Category	Decision-making authority
1	There is no single leader with decision-making authority; decisions are made with the entire project team
2	There is no single leader with decision-making authority; decisions are made with a leadership team
3	There is a single leader with decision-making authority but he/she is not competent
4	There is a single competent leader with decision-making authority

Diversity in knowledge/skills
For the diversity in different technological backgrounds, respondents will be asked how many different disciplines are combined in the project. To calculate the diversity, the Blau index will be used as used in for example Rushton (2008), for which the following formula is applied:

$$D = 1 - \Sigma j p_j^2$$

where D is diversity and p_j is the proportion of the total population from group j (Rushton, 2008). If the entire population is from a single group, D will equal 0. If the number of groups is increased, and the extreme case of each individual belonging to his or her own unique group occurs, D will approach 1 in value. So a higher value of D means more diversity. (Rushton, 2008)

Amount of funding
The amount of funding will be asked directly to the respondents and will be expressed in dollars, since the majority of the DIYbio community is based in the USA. Since projects were expected to differ greatly in the amount of funding, this variable was transformed to a logarithmic scale.

3.3.4 Overview of operationalization

Table 4 shows an overview of the operationalization explained in the section above.

Table 4. Operationalization of the dependent and independent variables.

Variable	Indicator(s)	Unit	Unit type	Variable type	Derived from
Project success	Effectiveness	0-100%	Scale	Continuous	(Lim & Mohamed, 1999)
	Satisfaction	0-100%	Scale	Continuous	
Degree of regulation	Regulatory density	0-100%	Scale	Continuous	(Klein et al., 2021)
	Uncertainty	0-100%	Scale	Continuous	
Technological novelty	Technology Readiness Level	0 = TRL > 4 1 = TRL <=4	Categorical	Binary	(Mankins, 1995)
Market size	Intended market size	1 - 4	Categorical	Ordinal	(Lüthje et al., 2005)
Presence of leader	Scale of leadership presence	1 - 4	Categorical	Ordinal	-
Variety in knowledge	Diversity in amount of disciplines involved in the field	Score between 0 and 1	Scale	Continuous	(Rushton, 2008)
Amount of funding	Amount of received funding in dollars	0 to ∞, in dollars	Numeric	Continuous	-

3.4 Data analysis

3.4.1 Qualitative data analysis

Interviews lasted between 30 and 90 minutes and were recorded and transcribed with the permission of the interviewee. The recordings were made using the free software Audacity, along with a backup recording in MS Teams or Zoom in most interviews. Transcribing was done in two steps. First, a transcript of the recordings was made using the free website www.otter.ai. Then, all transcripts were manually revised to change the literal transcript into readable sentences and to change names the software did not understand. The recordings and transcripts will be deleted after the completion of the research. To ensure that interviewees could speak freely, the identity of interviewees and any identifying information was made anonymous in the transcripts. A complete list of interviewees can be found in *Appendix E*. The transcripts were then coded with NVivo 20 using the Utrecht University license. The coding process was derived from grounded theory and entails open, axial and selective coding for information about the community. Additionally, the variables identified in the theory chapter provided six topics of interest which were used as a guideline for aggregating codes (e.g. 'Leadership' and 'Funding'). In the open coding process, 86 codes with 116 references were coded. In the axial coding stage, these codes were aggregated into 23 codes. In the selective coding process, four main categories were derived from these 23 codes. An overview of the coding trees can be found in *Appendix F*.

3.4.2 Quantitative data analysis

The data from the survey in Qualtrics was exported to an Excel file and made ready for analysis by cleaning up the data. This entailed deleting invalid entries to questions and duplicate or incomplete responses. Furthermore, the Blau index for the variable Knowledge diversity was calculated manually. The variables 'technological novelty' and 'presence of competent leader' were transformed to categorical factors, the categories which respectively indicate 'novel technology' and 'There is a single competent leader with decision-making authority' are expected to significantly differ from the other groups in the sample. The data was analyzed using the statistical programming tool *R*. Since the dependent variable of this study is continuous, a linear relation between the variables is assumed and therefore an Ordinary Least Squares (OLS) regression was performed. The *R* code of the transformation of variables and regression analysis can be found in *Appendix G.*

4. Results

In this chapter, both the qualitative and quantitative results are presented and analyzed. In section 4.1, the qualitative results are described in a narrative based on the interviews. The results are divided into the community characteristics and the relationships between the variables and project success. In section 4.2, the quantitative results are displayed and interpreted. In section 4.3, the hypotheses are accepted or rejected based on the quantitative results, supported by qualitative results for context and possible explanations for the obtained results.

4.1 Qualitative results

4.1.1. Community characteristics

Different cultures and backgrounds within the community

In the period 2005-2008 the term 'Garage biology' started being used to describe people who were *"building labs in pretty unusual places"* (Interviewee 1), exemplified by working in one's own garage. The idea was to *"think about life sciences outside of traditional spaces such as academia, industry or government and engage the population in a more broad and democratic way"* (Interviewee 1). For many people, this setting came from *"computer hacker spaces, more traditional hackerspaces"* (Interviewee 7). The terminology of 'hackers' is explained by Interviewee 2 who researched the term biohacker. The term hacker is defined as "someone who applies ingenuity to create a clever result, called a hack." (Levy, 2010), but ended up having the negative connotation of a hacker being "a malicious meddler who tries to discover sensitive information by poking around" (*Hacker*, n.d.).

In the US, the hype around 'garage biology' on one side and the negative association with hackers on the other hand led to two factors. The Massachusetts Institute of Technology (MIT) saw an opportunity to capitalize on the term garage biology and *"framed it as the next computer chip"* (Interviewee 4). At the same time, US government agencies were worried about biohackers since the negative connotation with the name caused suspicions about bioterrorism and the creation of biochemical weapons. The combination of these two factors led to a historical event where the FBI invited all known biohackers worldwide to a gathering at MIT in 2008 (Interviewee 1 & 7). It was at this meeting where 'the' DIYbio community was founded (from now on referred to as the MIT DIYbio community). The MIT DIYbio community is now phasing out the term DIY since it is associated with individualism while they want to promote collectivism, the new name being community biology (Interviewee 1).

US biohackers promoted commercialization of DIYbio projects from the start, approaching the whole idea of DIYbio as *"more business minded"* (Interviewee 4). However, there is also a lot of funding in the US which has allowed the community to continuously grow (Interviewee 2, 4). Since the founding of the community, interviewees 2,4,7 and 8 say that the US government through MIT funding is trying to keep some level of control over the community. This not only goes for the MIT DIYbio community but also for the iGEM competition, the international synthetic biology competition for high schools and universities (Interviewee 4). For the iGEM competition the US government influence does not seem to bother the participants (Interviewee 9). For the biohackers, the MIT DIYbio community is not the real community since they did not want to associate themselves with US government influence (Interviewee 2,3,4,7,8).

Among the most vocal opposers of the MIT DIYbio community are a group of European biohackers. The European DIYbio scene came up around 2011 because a group of like-

minded people started to meet up in Amsterdam where they randomly met through mutual connections (Interviewee 4, 7). In 2011, it was all about discussing and experimenting with technologies in their free time, for example Interviewee 4 *"we started meeting up on Tuesday nights and talked about what we thought was interesting."* (Interviewee 4). At first, experimentation was the only focus: *"we were making a lot of stuff without any pre-constructed ideas"* (Interviewee 4) and *"I then saw a script of the university of a bioreactor, in which it was more or less explained how it worked. And so I was like, let's build a lab device in my free time."* (Interviewee 7) highlight this. There was even a high resistance to commercialization because it felt like selling out. Interviewee 4 says that after trying to commercialize a project they were working on *"the European community completely disagreed and turned on me, making me ridiculous on forums and mail groups.".*

Eventually the community realized that their ideas were fit for commercialization and founding a startup from a DIYbio idea became more accepted. This resulted in the majority of the group founding startups like Digi.Bio, KiloBaser, Nordetect and SwissDeCode (Interviewee 4). The group feels like this was the peak of DIYbio in Europe, *"the peak was in 2013-2015, when there was a group of founders who know each other, like a group of biohacking space founders, or at least active biohackers, who all knew each other"* (Interviewee 7). They think that there is no next generation of people in Europe who are doing the same as them (Interviewee 4,7). Interviewee 8 *"jumped into the community in 2017"* but he is working with people who were involved in the community from the start (Interviewee 8). Interviewees 4 and 7 say that there is a change in mindset in the community from only experimenting to a more commercial mindset, which is confirmed by Interviewee 8.

A third group of biohackers with a different culture and background can be found in the rest of the world, especially in developing countries. Since 2017, DIYbio labs and communities have been founded in countries in South America, Africa and Asia (Interviewee 1, 4, 5, 9). There are often urgent problems in the country on top of the challenges that can be addressed with synthetic biology technologies. The home countries of Interviewees 5 and 9 are, for example, affected by an economic crisis, an energy crisis or a malfunctioning government (Interviewee 5,9). Also, these problems lead to a 'brain drain', where *"if students want to stay in science, they usually go abroad to get postgraduate degrees and stay there to work in industry"* (Interviewee 5). There is a need from people in the country to tackle these problems themselves, for example in Peru where *"the solutions that the government gave to address the problems are basic solutions. And our project was a unique solution for one problem that affects most of the people here because there are thousands, if not millions of Peruvian people who are farmers"* (Interviewee 9). Founding labs and creating communities helps in organizing projects to tackle these problems (Interviewee 5,9).

Figure 3 presents a stylized representation of growth of the community over time based on the descriptions of the interviewees, split into the three distinct geographical groups that were identified. The size of the community is a rough estimation based on the interviewees and the participants of the Global Community Biosummit. The European part of the community slightly decreased after the first generation of biohackers started being less active.

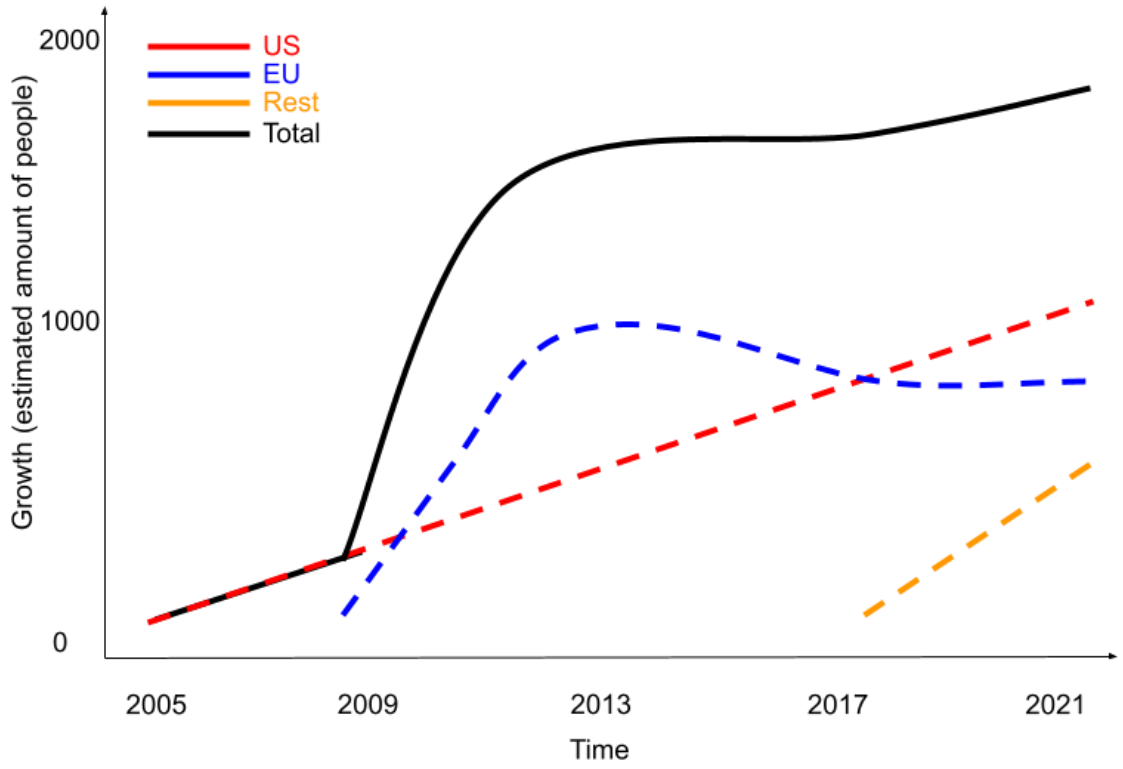

Figure 3. Community growth over time in different parts of the world and total

Next to the differences between parts of the world and motivation, there is another divide in the community. As Interviewee 2 explains: *"Something to understand about this community is that it is actually heavily split in two streams as far as I am concerned. There are two kinds of people: on one hand there are the pragmatic/entrepreneurial/technological people and on the other hand the artistic types/awareness enthusiasts"*. While it may seem that the technologically minded people have started DIYbio, bio art has been a part of the community since the beginning, and as Interviewee 7 explains it has also helped the technological side of the community gain traction since the beginning: *"there were a couple of meetings actually, where we met in Denmark or Switzerland for example. The bio artists organized these because they were kind of working full time. I was working on getting funding so I did not really have time to organize meetings. So often this Bio stuff was like a side of the bio artist meetings."*. Interviewee 4 states that *"European DIYbio has increasingly been going into the direction of Bio Art."* and Interviewee 8 explains this: *"In Europe, we have a lot of funding for bio art. And so we allow this scene to flourish better while in the US I don't think so."*. Interviewee 7 adds that bio art may also be more accessible to people: *"maybe that's a reason why there's probably more bio artists then biohackers in that sense, because it's much easier to do some art and leave it for a couple of days, rather than working on a hardcore science project every day."*. Although biohackers have different motivations and cultures there are characteristics they all share, these are presented in the next section.

Similarities within the community

The biohacker/DIYbio community is a complex and global network of individuals who are connected through mutual links. While there are many differences between labs, countries and individuals, there are shared community characteristics which the majority of the interviewees mentioned or described.

Interviewees indicated that DIYbio often starts with dissatisfaction with their current job or job prospects. Biohackers often have an academic background and then work in the

biotechnology industry, but at some point in the process decide that it is not for them, for example *"after my thesis I wanted to do something myself but I did not want to work in the industry."* (Interviewee 2), *"After my studies I went to Amsterdam to work for a large company, but it was very repetitive work which I did not enjoy."* (Interviewee 4) and *"My goal was to work in sustainability, but I wanted a more independent setup, not working at the university. So I wanted to enjoy more freedom to choose my own topic and set my own challenges"* (Interviewee 8).

Biohackers also share a certain degree of critique on society or activism. As Interviewee 4 states, DIYbio initiatives are often *"rebellious against society as a starting point".* Fundamentally, all interviewees agree on *"thinking about life sciences, outside of traditional spaces outside of academia, outside of corporations outside of government, and really starting to engage the population in a more broad and democratic way"* as the definition of what they are doing, mentioned before (Interviewee 1). Interviewee 8 adds: *"we want more technologies that bring advantages to the most and not get patented, so it can be used to reduce inequality between the wealthy and poor"*.

Other Interviewees, however, are more extreme in voicing their opinion. For example, Interviewee 4 said: *"the main path for creating new technologies is either industry or academia, but not a lot of real new technologies actually come from these groups. This system has lost its way in the sense that a lot of promising ideas do not make it due to idiotic internal struggles."* and substantiates this by explaining that the exact idea for his own startup was pitched at a large firm but never made it due to internal conflict. Interviewee 7 is more critical of the education system: *"I really hated the way that the education system works, teaching at universities. The fact that the challenge is learning shitloads of theory, and not anything else really. That was the whole point of the open bio lab, we wanted a place where we could just do something and not just, you know, read books"* (Interviewee 7).

The dissatisfaction with their own job and critique on society then often lead to two actions: searching for and meeting with like-minded people and starting to experiment in their free time. The interviewees describe that *"the common denominator is having something in common with other people in the community"* (Interviewee 2)*, "and we are based on very similar values. When I look at our values on paper, or how we operate at least, I think it's pretty similar. we are all motivated by participating in scientific matters* (Interviewee 8) and *"I mean, it's definitely bound together by the excitement for the technology, right?"* (Interviewee 6). After meeting people locally, biohackers start interacting with the international community: *"You didn't know that you had so many people from all around the world that share your value system and care about the same things that you do, and they are all of a sudden brought together into one room for the very first time. "* (Interviewee 1), *"meeting with people abroad in Asia, and I was with three people from Africa, we all have kind of the same mindset."* (Interviewee 8) and *"I got in touch with the international bio community because of a search online and I found out: 'oh, there's more than us.' This was back in 2013. It wasn't much more than us, but there were a couple of other labs worldwide. But it was pretty cool to discover that."* (Interviewee 7).

After finding like-minded people, a place to experiment together is needed. Finding a suitable place can be challenging for individuals, as mentioned by Interviewee 5: *"one of the main challenges our community is facing is that existing labs are not really open for people to go and experiment"* and *"in university, we are not able to experiment outside of practicals and then we don't have a good time like playing with the instruments on our own"*. Interviewee 7 agrees and indicates that this also was the case when starting in 2011: *"It's not like you have to finish something you know, it's more to get some basic experience and just learn a bit. I think It's a pity that not every university has an open lab, or at least every biology university. That there is not someplace we can go and practice or do some experiments."*.

Another shared trait between biohackers is that they are quite entrepreneurial and can achieve

a lot with few resources. Interviewees indicate that due to the lack of free experimentation space, they decided to build a lab themselves (Interviewee 2,3,4,5,6,7), accurately described by Interviewee 7: *"And then after a couple of months, or even a year, I was like, why don't we have our own lab? Similar to these computer hacker spaces? Why don't we have a free access lab for everyone?"*. Once some kind of lab space is available and biohackers can experiment freely, the entrepreneurial mindset remains: *"We started experimenting and I thought that one of our ideas had a lot of potential so I thought the natural next step was to try and start a firm."* (Interviewee 4) and *"we joined a program with the idea we were developing and got like $30,000 for joining the program, which was a lot of money for us back then, of course. Me and my two co founders, we were still students. So this is how the company started"* (Interviewee 7).

Overall, the international community consists of three different groups: the US where funding from the government enables constant growth but limits independence, like a franchise model. In Europe, DIYbio initiatives are more independent from governments but lack constant growth. In countries in Asia, South America and Africa problems are addressed because government action is lacking. The groups are connected through dissatisfaction with their jobs, a degree of activism, the urge to seek like-minded people, experimenting in their free time and an entrepreneurial mindset.

4.1.2 Project characteristics and conditions

The overview of the community provided in section 4.1 helps to analyze the relationships between the independent variables and project success. First, the relationship between technology, market and regulation and project success are explained using examples from projects described or mentioned by interviewees and used to sketch a figure of the dynamics of the DIYbio project ecosystem. Next, the relationship between leadership, funding and knowledge diversity and project success is described and used to create an overview of key activities in leading a DIYbio project.

Technology

The statement which all interviewees supported and emphasized was that every DIYbio project is different and therefore uses different technologies and has a different relation to technology. Based on the projects described by interviewees, two dimensions can be identified on which to differentiate projects in relation to technology. The first dimension is what is done in the project, either application or development of technology. In the application of technology, a new use or business model is applied without further improving the technology itself. In the development of technology, a technology is further developed in the project. The second dimension is the motivation to start the project. A project can start without a clear purpose other than experimenting with synthetic biology or can be a personal interest in a certain technology. There can also be a very clear purpose for the project or a specific problem that is set out to be solved. The two dimensions are projected in *Figure 4* displayed below, along with the archetypal examples of projects in every quadrant. The examples are explained below *Figure 4*.

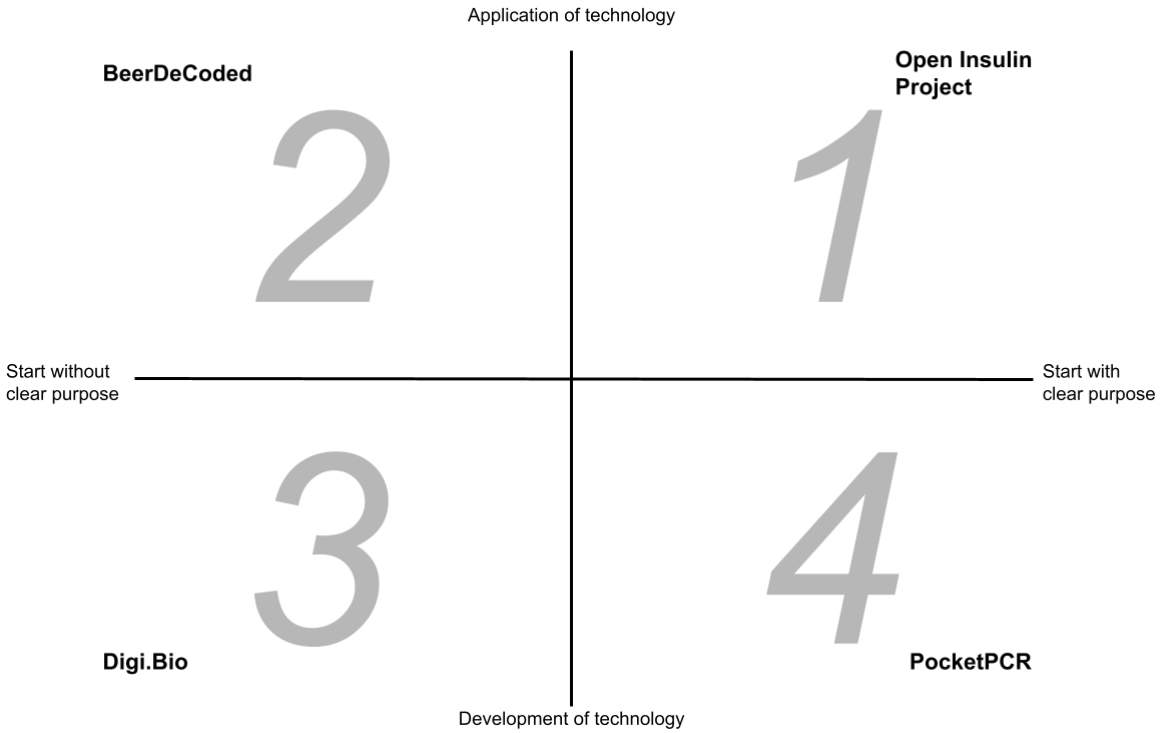

Figure 4. Dimensions of how technology is used in DIYbio projects.

Quadrant 1: Application of technology with a clear purpose
Interviewee 3 mentions The Open Insulin Project, of which the goal is to transform a business model around an existing technology, namely creating an open-source model for insulin production that centers on sustainable, small-scale manufacturing and open-source alternatives to production (Open Insulin Project, n.d.). Both the insulin production methods and equipment already exist, but the project is aimed at finding a way to produce it on a small scale (*Open Insulin Project*, n.d.).

Quadrant 2: Application of technology without a clear purpose
Interviewee 2 mentions that DIYbio *"is combining technologies, not often novel technologies but repurposed technologies, it is like being a good DJ, using existing tracks but mixing them together in a new and exciting way"*. An example mentioned by Interviewee 4: the BeerDeCoded project which captured the metagenomic profile of 39 bottled beers using next generation sequencing (Sobel et al., 2017). While the project started out for fun, the people who started the research are now trying to collect more data and claim that further analysis could shed light on the 'microbial dark matter' of the beer ecosystem, already engaging with small breweries to do further research (Sobel et al., 2017).

Quadrant 3: Development of technology without clear purpose
An example mentioned by Interviewee 4 is Digi.Bio, which is a firm using digital microfluidics for fine-grained experimental control (*Digi.Bio | Making Biology Programmable*, n.d.). It began with *"a bunch of nerds talking about what we thought was interesting"* (Interviewee 4) but in the end Interviewee 4 says Digi.Bio has *"contributed a lot to the development of technologies like digital microfluidics and PCR."* (Interviewee 4).

Quadrant 4: Development of technology with clear purpose
A barrier to using certain technologies mentioned by lab founders was that lab equipment for even the most simple synthetic biology technologies is expensive (Interviewee 2,4,5,6,7). Taking this barrier away is one of the community's main missions: *"a large part of these*

projects are about accessibility, so making expensive or complex technologies available to the greater public" (Interviewee 2). Multiple examples of projects were mentioned by the interviewees: *"I found out that it is really old, like 40 years old, the underlying hardware for DNA synthesis. And so we're like, 'hey, let's build an open source version.' So we made a biohacker version of a DNA synthesizer"* (Interviewee 7) and *"a lot of the developments he did were also aimed at making existing technologies more accessible, he created the pocketPCR for example."* (Interviewee 4). Other than the personal DNA/RNA synthesizer and pocketPCR, technologies that were mentioned by interviewees were OpenPCR, a PCR Thermocycler, OpenDrop (digital microfluidics) and OpenTrons (lab robots) and countless 3D print designs for lab equipment like tube holder.

Market

In line with *Figure 4*, whether clear project goals are present influences the intended target market of the project. Projects without a clear purpose start out with an individual or team who experiment without commercialisation purposes and then turn out to be useful for more people, such as the BeerDeCoded and Digi.Bio examples (Interviewee 4). At first, the intended market is individual or project team use, but the end product can have a specific target market, such as beer breweries for BeerDeCoded and people or firms who need to precisely manipulate droplets at a microscale.

On the other hand there are projects with a clear purpose from the start of the project. These projects are usually already aimed at a bigger and more general intended target market. One such target market is other biohackers, for whom technologies like the PocketPCR are developed to run their labs (Interviewee 2,4,5,6,7). Since the goal also is to make technologies accessible to 'the general public', making technologies easy to use and cheaper will also cause the DIYbio community and therefore the target group to grow. The Open Insulin Project also has a large, general and growing target market: diabetes patients. The target market can also be local groups, such as the Peruvian farmers mentioned by Interviewee 9 or households in Sri Lanka mentioned by Interviewee 5.

In *Figure 4*, it seems that projects can be divided in quadrants in a static manner. However, when taking the intended market into account it is clear that projects change over time. In this sense, the x and y axis can be seen as continuous, with projects changing position over time. While a project like BeerDeCoded started without a clear purpose, it does have one now. The other way around, a project like the Open Insulin Project started with a group of people with a less clear goal in a community lab called Counter Culture Labs (*Open Insulin Project*, n.d.). An example of a project which currently is looking for a clear purpose is Benzyme Ventures, a community in Sri Lanka aimed at building a bioeconomy in the country, which is *"still figuring the basic stuff out"* according to interviewee 5. *Figure 5* below therefore presents a more dynamic model, in which projects can move from the top left of the figure to the bottom right: from an unclear purpose and finding applications for existing technologies towards a clear purpose and developing technologies. The diagonal line displays the direction of change over time for the relation to technology, purpose of the project and intended target market.

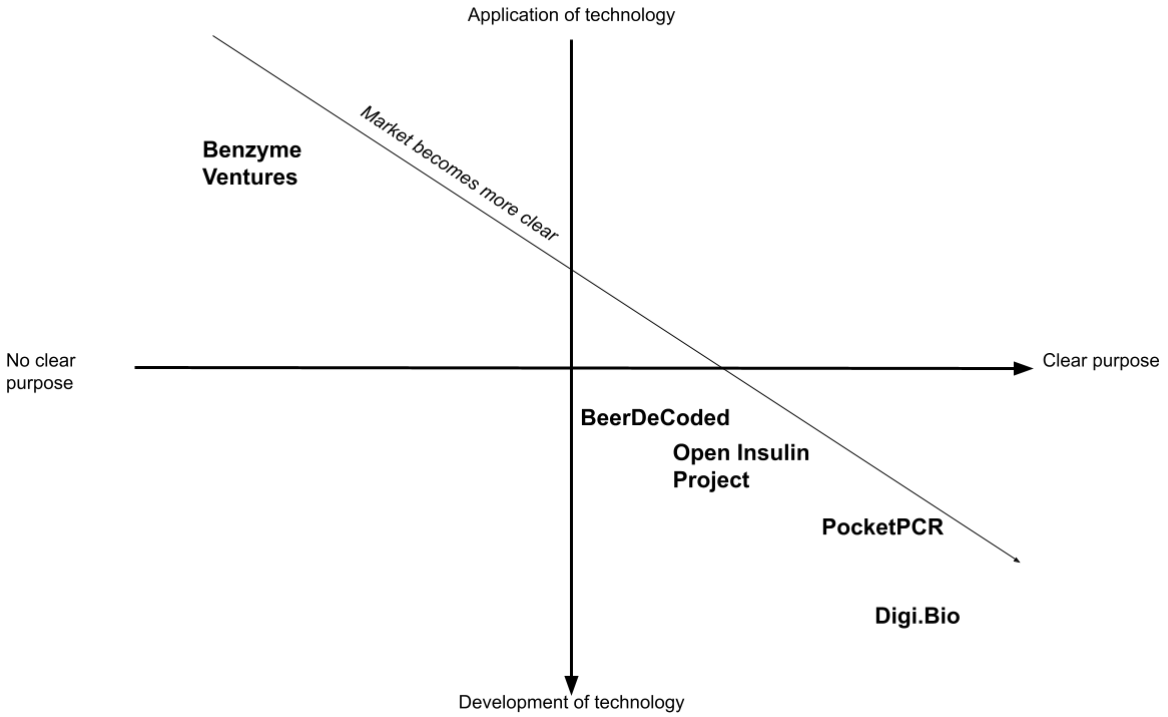

Figure 5. Dynamic model for state of DIYbio projects.

Regulation

In terms of regulation, interviewees said it was logical that lab and safety protocols are always in place (Interviewee 2,3,5,6,7,8,9). Protocols are enough for experimentation in labs and for the majority of DIYbio activity (Interviewee 2). When having a proof of concept and the will to pursue the idea further, other regulations started to play a part in their activities but not in a negative way (Interviewee 4,7). Overall, the relation to regulation changes over time, just like the intended target market. When there is no clear purpose and application of technologies, there are existing protocols in place for the technologies used which have to be adhered to. When moving to a clear purpose and developing the technology, adherence to more regulation is needed, also dependent on the intended target market. For the PocketPCR, competing with the commercial PCR machines meant that it had to adhere to the same specifications to allow the same types of experiments to be carried out, such as temperature control and preventing sample evaporation (*PocketPCR – The Thermocycler for the Rest of Us*, n.d.). The Open Insulin Project is even researching new regulatory pathways to allow their decentralized small-scale production model to reach patients (*Open Insulin Project*, n.d.).

There are also people in the community who only stay in the experimentation phase and have fun in trying to develop open source technologies for others without ever having commercial intentions. Interviewee 4 gives the example of GaudiLabs, which is run by someone who likes developing technologies but does not aim to profit and moves on to the next project before something is done with the newly developed technology (Interviewee 4). Other people then take these technologies and commercialize them (Interviewee 4). In *Figure 5*, these people would fit in the bottom left quadrant, since they are developing technologies but do not have a clear purpose for the project.

On the other side of the spectrum there are the bio artists. A big role of bio art is to stimulate the ethical discussions around these synthetic biology technologies which often concern modifying genetic material: *"bio art brings the human component back to technology. Science is basically technology and philosophy combined but this philosophical component is heavily underdeveloped in our society, bio art brings this component to light."* (Interviewee 4).

Interviewee 8 gives the example of a bio art project called Semina Aeternitatis, in which a human memory is written down and then translated into a DNA sequence using an algorithm. This was then manufactured as a plasmid, creating a bacteria carrying a human memory (*Semina Aeternitatis*, n.d.)**.** Interviewee 7 also explains that it can even help in introducing people to the positive sides of genetic engineering: *"people are very much opposed here to genetic engineering, especially green biotech, like the agriculture engineering. so it's also political, the movement or the lab we have because we want to educate people around these amazing technologies"*.

There are, however, also critiques on bio art: *"I think this is something the community is currently doing wrong. It's the same as in my hometown, artists are nice and inspiring but most of the time technologists are more introverted and artists are more extroverted. Then the artists start screaming 'look at me' and the technologists are scared off by this. Then the only thing that remains is people who raise awareness and scream loud but no really cool biotech ideas/startups."* (Interviewee 2). Interviewees 4 and 7 agree: *"However, there are also a lot of artists nowadays who just try to grab attention and do not really contribute anything useful."* (Interviewee 4) and *"in many cases, I feel like artists just try to catch attention for things which are not not on a technological level interesting at all. So kind of drawing the attention from, let's say, meaningful products to pay for our art"* (Interviewee 7).

All in all, bio art is considered useful to the community when done right. Since bio art is typically a different application of an existing technology, and the purpose of sending a message is clear, bio art fits in the top right quadrant of *Figure 5*.
Figure 6 displayed below shows the addition of how projects relate to regulation over time. Also, pure open source technologists without commercial aims and bio artists can now be added to the model, also presented in *Figure 6*.

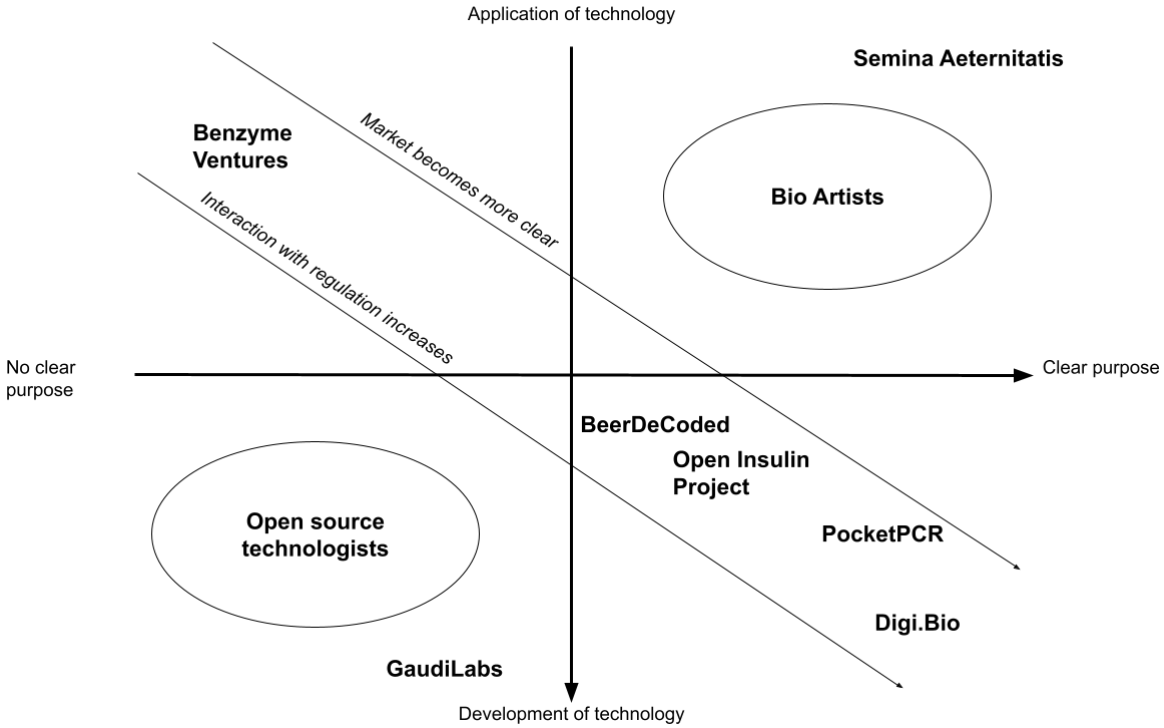

Figure 6. Dynamic model of DIYbio projects with pure technologists and bio artists added

Finally, the groups within the model also interact with each other. Four interactions are distinguished between commercial, open source technology and bio art projects. The interactions are described below, followed by Figure 7 in which the interactions are added to

the model.

Interaction between successful commercial projects and open source technologists
First, successful projects have lots of useful resources to give back to the community, as Interviewee 4 says: *"the community has allowed me to be in this place so I try to give back where I can"*. Giving back can be done in multiple ways such as making intellectual property free to use, sharing knowledge in workshops or at community gatherings or even funding new projects.

Interaction between successful commercial projects and bio artists
Successful projects also means that new technologies and applications of technologies are developed, which often have to do with a form of genetic manipulation, giving artists the ability to both use the technology for art and to reflect on these new developments.

Interaction between open source technologists and new projects
Open source technologists are in turn great for the community, since they develop technologies for others to use freely or for only resource costs. This provides a great infrastructure and support for people to experiment freely with.

Interaction between bio artists and new projects
Interviewee 8 explains that bio art is a source of inspiration for technological innovations: *"the cool thing is that from these ideas, scientists get inspired, I actually actively engage in this. So I teach people how to work with mushroom based materials, and then let a lot of artists play. And from them, I get a lot of inspiration, actually"*.

Figure 7 displays the final model with the added interactions. The exact projects used as examples are not displayed anymore, but a general project cycle is described in the DIYbio project ecosystem. The phases described in Chapter 2 are used to indicate the phase of the project: discovery, development and diffusion.

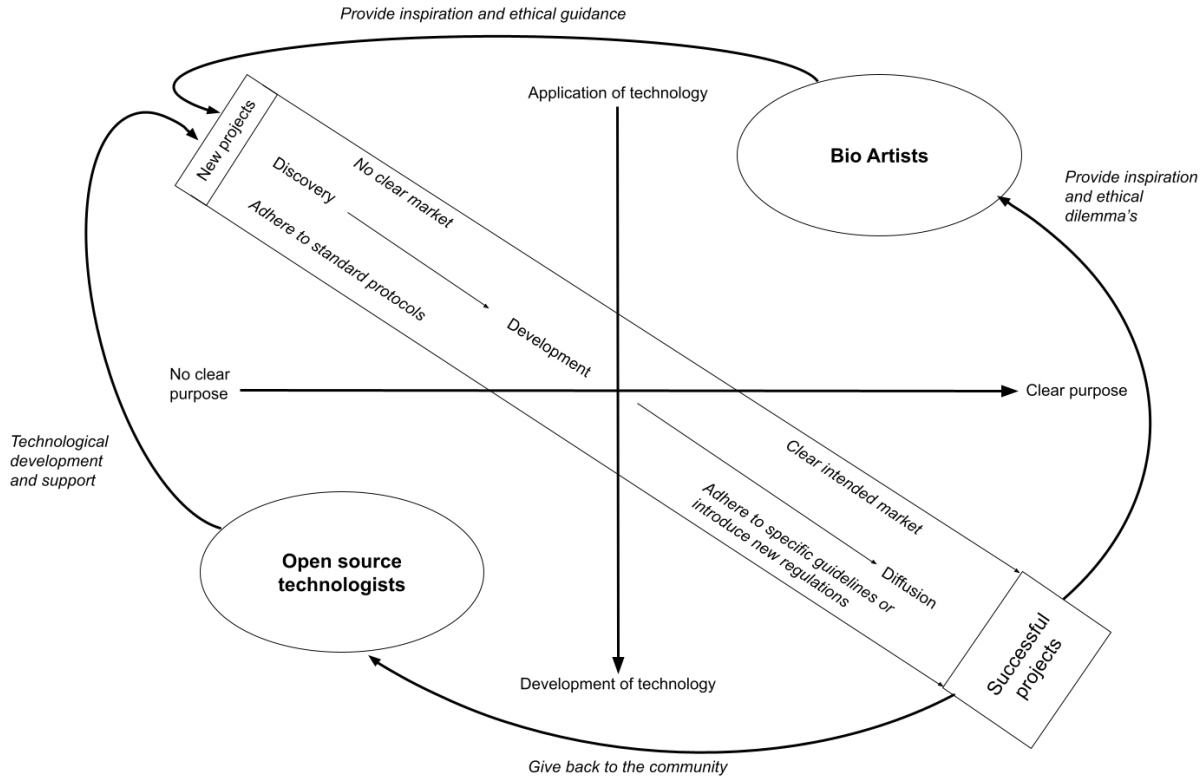

Figure 7. Dynamics of DIYbio project ecosystem.

Leadership

Interviewees highlighted servant leadership as the most important leadership style for DIYbio projects and labs in general. Interviewee 2 describes good leaders in the community as "*servant leaders who enable others to excel. They try to remove barriers for others.”*. Interviewee 1 describes it as *“this community is like a bunch of pirate ships. There is no CEO, it's not a classic hierarchy. It's not like anybody can say, ‘go do this or that’ everyone is going to do what they want to do. And for me, I think one of the big questions is, how do we serve these communities”.* Interviewee 6 who is managing a lab, adds: *“the idea is that we have access to this pool of funding so that we can rent a space and bring the equipment together. That's what my role is right now.”*.

An important characteristic of a leader is the ability and willingness to build a network, which almost all interviewees recognize. Interviewee 5 explains the process: *“So what we did was we initially wanted to connect with these people. And then through personal contacts and friends, we reached out to people who graduated and were working in other countries and we started doing this kind of talk show. Then we can build a pool of researchers like postgraduates who are already in universities. And then we connect the students to researchers and start a mentoring session. And last month we found a physical place to start the lab so right now we are sorting out the basic stuff.”*. Other important factors are *“technical preparation and experience. Because you need to get everything together.”* (Interviewee 8). Finally, Interviewee 7 explains that for one of these projects to be successful, a lot of time and perseverance is needed: *“I think what we learned, or what many of us learned was that to really get something done in biology, it takes a vast amount of attention and time. And then there were very few people being able to dedicate so much time, effort and and also money to some extent, to get a project really done. So it's tough to do biology as a hobby, it's really tough.”* (Interviewee 7).

Altogether, leaders of DIYbio projects must first provide a lab space with room for free experimentation and equipment with clear manuals and protocols. The leader should have experience with the technologies that are worked with. At the same time, building a network helps in covering the aspects of a project in which the project leader is less experienced. To relate back to Chapter 2, it seems that DIYbio leaders start in the same way as OSS leaders with ‘real authority’, providing the starting point and having legitimacy because of their experience and network. Once an idea shows potential, leaders should focus on having a clear purpose for the project. Then, funding should be acquired through crowdsourcing or venture capital and regulations to which the product has to adhere have to be taken into account. In this stage, it seems that leaders need more formal authority as they interact with venture capitalists and regulatory parties and need to make sure goals are reached and regulation is adhered to.

Lab and project funding

The DIYbio community consists of a large number of labs, which all have different proportions of paid and voluntary work. As Interviewee 3 explains: *“On one hand there is something like Counter Culture Labs which is completely run on volunteers and has been for years, so this works for them. On the other hand there is GenSpace, which has been tracking all of their contributions over 2019 and tried to quantify this. All the other labs can be placed on a spectrum between these two labs.”*.

Both ends of the spectrum have their advantages and disadvantages. Interviewee 3 explains that a lot of labs are having a hard time to keep their operations going, which was only strengthened by the COVID-19 pandemic (Interviewee 3). Interviewee 3 therefore looks up to GenSpace and their quantification method, since *“this resulted in an overview of community outreach and list of projects and contributions to the neighborhood. They presented this to the municipality of New York and gained a lot of funding from them.”*. The quantification method

of GenSpace entails tracking the amount of people engaged in their courses and development programs, for example stating that they have engaged with 768 learners in 14 new classes (*GenSpace Annual Report*, 2020). The quantification of the outreach results in $251,180 of funding from foundations and local governments, which is half of their total income (*GenSpace Annual Report*, 2020). Interviewee 3 therefore states: *"To me it would be very interesting to see if a standard set of indicators can be made for community labs with which they can quantify their work and gain funding."*.

However, Interviewee 6 explains why gaining funding also has its merits for a community lab: *"I think that in the case of genspace, because they've quantified everything, they've also fixed themselves in a certain way of being and now they have to deliver on the things that they quantified and continue to deliver on the things that they've quantified. So in some ways, like the type of projects that exist inside of that space are fundamentally different than the types of projects that exist inside of Counter Culture Labs."*. Interviewee 6 continues that there could be similar projects going in both labs, but that *"it won't actually affect the end result, I think it's just become more expensive. Actually, that's all that's happened at GenSpace, because they have paid staff and their model is geared to provide the educational framework. So then it's just become more expensive, actually, to do some amount of research. For example, the project that I'm doing here, it might be possible to do it at Genspace, but I would have to work through their staff to understand the liabilities and things in a way that I don't have to work through the staff here."* (Interviewee 6). The main driver for the voluntary lab model therefore seems to be to keep autonomy and freedom in what to experiment with.

Interviewee 5 explains that he is trying the voluntary model in his lab: *"we reached out to them, and then we said 'we are a community that wants to work in research and develop these things, so if you have projects that you don't have funding for, we would like to volunteer and come to your lab, and push the project to the next level."*. Interviewee 6 expands on the voluntary model*: "I think the voluntary part intersects with more activism style thoughts, right? because it's voluntary it means that there's no incentive anyways. I like volunteering only, but, when I think about volunteer run organizations that operate shared infrastructure, my first experience comes from, like a community garden, which almost is structured a little bit like a mutual aid group style, like people pay like a small fee. And then they have to do gardening tasks because they have to volunteer. I think maintaining a lab is a little bit more complicated. And the operating costs are a bit higher, especially in New York City, it's more expensive to rent physical space than to have a garden. So I'm not sure whether or not this model will apply to renting a space in New York City, but that's the experiment right now."*. Finally, Interviewee 6 gives a well-formulated conclusion on the paid versus voluntary lab model discussion: *"In the excitement over DIYbio, everyone wants to take the best parts of it and brand themselves, but they have different sources of funding. And that means that brings different incentives to the table."*.

On top of running a lab and projects, some people try to commercialize their ideas. For this, additional funding is required. Some products were able to be developed by donations, own investments and/or crowdfunding, but others needed venture capital. Interviewee 7 indicates that they found an accelerator program: *"we needed some cash. So in a bio community online forum, I found an advertisement for what is now called the Indie bio accelerator program. It's a pretty, pretty known program now. At least in the bio space. Also, a lot of former biohackers went through the programs. And so we're like, let's join, we got like, $30,000 for joining the program. And after the program, we got a larger investment from a venture capital company and this is how things got going around the company. "*. Interviewee 4 indicates that he got his funding from the same venture capital company: *"This was not possible without the help of SOS Ventures, who basically believed in people and invested in multiple startups which came from DIYbio projects."*. Indie Bio is the biotech branch of SOS Ventures and has been active since 2014, stating that they are *"the first accelerator to systematically write small checks into radical ideas using biology as a technology to disrupt markets"* (*Indie Bio - Program*, n.d.). It

therefore seems that the nature of this program is well suited for DIYbio projects.

Knowledge diversity

As interviewee 1 highlights: *"I think one of the really unique things about DIYbio is the integration of Life Sciences, synthetic biology, biotechnology, but specifically with movement building, organizing tactics."*. All interviewees agree that this diverse pool of people with different expertises helps in running labs and projects, and also helps in setting up startups. In terms of running labs, an example is found in Counter Culture Labs, who state *"we believe in the power of diversity and peer-to-peer education; everybody has something to teach and everybody has something to learn."* (*Info & History*, n.d.). For startups, Indie Bio states that their 199 alumni actively share their knowledge and that, comparable to other incubation/accelerator programs, they offer mentoring and access to their entire network (*Indie Bio - Program*, n.d.).

Figure 8 below presents the activities that are undertaken in the different stages of a successful project, enabled by a leader and enhanced by diversity in backgrounds from the project team and network. The activities are based on the mechanisms described in the section above and are a synthesis of the results.

Discovery	Development	Diffusion
Meet and discuss with peers	Develop product	
Build network	Use network for help	
Search for applications of technology	Develop technology	
Promote free experimentation	Set clear purpose for the project	
Experiment with own interests	Identify target market	
Acquire lab funding & equipment	Acquire venture capital	
Adhere to basic lab protocols	Adhere to regulation or propose new	
Make use of community resources		Give back
Be inspired by bio art		Inspire bio art

Figure 8. DIYbio project activities that enable success

4.2 Quantitative results

4.2.1. Descriptive statistics

Table 5 displayed below shows the descriptive statistics of the continuous variables.

Table 5. Descriptive statistics of continuous variables

	Success	Funding (log)	Knowledge diversity
Lowest	0	0	0
Highest	0,98	15,6	0,9
Median	0,66	9,21	0,52
Mean	0,62	7,89	0,52

Table 6 below shows the names and counts (between brackets) of the categories of the categorical variables.

Table 6. Descriptive statistics of categorical variables (N = 32)

Value	Technology	Market	Regulatory Density	Leadership
0	Novel technology (21)	-	-	-
1	Mature technology (11)	Individual or project team use (1)	Perfect regulatory equilibrium (7)	There is no single leader with decision-making authority; decisions are made with the entire project team (9)
2		Local or DIYbio community (4)	Regulatory equilibrium (5)	There is no single leader with decision-making authority; decisions are made with a leadership team (8)
3		National market (6)	Regulation is a barrier (11)	There is a single leader with decision-making authority but he/she is not competent (2)
4		Global market (21)	Existing regulation is not sufficient (9)	There is a single competent leader with decision-making authority (13)

4.2.2. Regression results

The following chapter presents the results of the regression analysis on the data obtained by the survey. Table 7 presents below the results of regression models between the independent variables and project success. The only models that have significant results are models 1, 5 and 6 which are regulation, knowledge diversity and leadership respectively. Model 1 shows that compared to perfect regulatory equilibrium, regulatory overshoot (regulation is seen as a barrier) has a significant negative effect on project success at $p < 0.1$. Model 2 shows that all other intended market categories have a lower project success compared to individual use, however the results are not significant. Model 3 shows that there is almost no difference between using a novel or a mature technology to make a project successful; these results are also not significant. Model 4 shows the same for funding, funding does not significantly influence project success. Model 5 shows that higher knowledge diversity in the project team positively influences project success and is significant at $p < 0.1$. Model 6 shows that

compared to making decisions with the entire project team, having an incompetent leader has a significant negative effect on project success at $p < 0.1$. The adjusted R squared of the significant models 1,5 and 6 are 0.137, 0.069 and 0.057 respectively, meaning that the models have very weak explanatory power.

Table 7. Regression analysis between independent and dependent variables. Table made with stargazer (Hlavac, 2018)

Regression results

	Dependent variable:					
	Project Success					
	(1)	(2)	(3)	(4)	(5)	(6)
Regulatory equilibrium	0.002					
	(0.142)					
Regulation is a barrier	-0.213*					
	(0.118)					
Existing regulation is not sufficient	0.078					
	(0.123)					
Local or DIYbio community		-0.227				
		(0.291)				
National market		-0.406				
		(0.281)				
Global market		-0.220				
		(0.266)				
Mature technology			0.040			
			(0.099)			
Funding				0.014		
				(0.011)		
Knowledge diversity					0.373*	
					(0.205)	
Leadership team						-0.022
						(0.124)
Incompetent leader						-0.395*
						(0.199)
Competent leader						0.028
						(0.110)
Constant	0.670***	0.867***	0.605***	0.504***	0.426***	0.637***
	(0.092)	(0.260)	(0.058)	(0.101)	(0.115)	(0.085)
Observations	32	32	32	32	32	32
R^2	0.220	0.108	0.005	0.051	0.099	0.148
Adjusted R^2	0.137	0.013	-0.028	0.020	0.069	0.057
Residual Std. Error	0.243 (df = 28)	0.260 (df = 28)	0.265 (df = 30)	0.259 (df = 30)	0.253 (df = 30)	0.254 (df = 28)
F Statistic	2.640* (df = 3; 28)	1.135 (df = 3; 28)	0.161 (df = 1; 30)	1.620 (df = 1; 30)	3.306* (df = 1; 30)	1.625 (df = 3; 28)
Note:						*p<0.1; **p<0.05; ***p<0.01

To increase the explanatory power, models with multiple independent variables were created. These are displayed below in *Table 8*. Model 1 includes only regulation and leadership, Model 2 also includes knowledge diversity. Models with only regulation and knowledge diversity or leadership and knowledge diversity were not worthy of showing since the results were all insignificant. Model 2 shows that when adding knowledge diversity, the other effect sizes, significance and adjusted R squared are all reduced. Therefore, Model 1 is the strongest model that can be made with the data of the survey. Model 1 shows that regulatory overshoot and having an incompetent leader both have a strong negative effect on project success at $p < 0.05$. The adjusted R squared of Model 1 has increased to 0.186 compared to the separate models (0.137 and 0.057), but still indicates a very weak explanatory power.

Table 8. Regression models with the best fit. Table made with Stargazer (Hlavac, 2018)

Regression models

	Dependent variable:	
	Project Success	
	(1)	(2)
Regulatory equilibrium	-0.054	-0.046
	(0.151)	(0.154)
Regulation is a barrier	-0.252**	-0.231*
	(0.118)	(0.127)
Existing regulation is not sufficient	0.021	0.025
	(0.125)	(0.127)
Leadership team	-0.074	-0.089
	(0.119)	(0.124)
Incompetent leader	-0.410**	-0.363
	(0.190)	(0.212)
Competent leader	-0.066	-0.052
	(0.111)	(0.115)
Knowledge diversity		0.132
		(0.247)
Constant	0.779***	0.696***
	(0.123)	(0.200)
Observations	32	32
R^2	0.343	0.351
Adjusted R^2	0.186	0.162
Residual Std. Error	0.236 (df = 25)	0.240 (df = 24)
F Statistic	2.179* (df = 6; 25)	1.855 (df = 7; 24)
Note:		*p<0.1; **p<0.05; ***p<0.01

Model 1 was checked for outliers, multicollinearity and heteroskedasticity to improve the model fit. Two cases were identified as outliers because of a low project success score, but removing these could not be justified as the measurement was done correctly and the scores were possible in the context of this research. The VIF score for both regulation and leadership was 1.4, meaning that no multicollinearity was present. The studentized Breusch-Pagan test was not significant (0.1844), meaning that the hypothesis of heteroskedasticity being present can be rejected.

4.3 Analysis

Hypothesis 1 stated that a moderate level of regulation would lead to an increase in project success. The qualitative results explained that DIYbio projects all have a baseline of regulation in terms of lab and material safety protocols, this is not seen as a barrier but as a logical aspect of their experiments. A part of the community stays in this experimentation phase and has no ambitions to commercialize ideas. For the part that does see potential in their ideas and wants to commercialize them, adhering to regulation starts to become important. Some projects even help shape new regulatory pathways. The quantitative results showed that when regulation is

seen as a barrier (regulatory overshoot), this negatively impacts project success. However, no indication of a positive effect of moderate regulation (regulatory equilibrium) on project success was found; H1 is therefore rejected.

Hypothesis 2 stated that experimenting with a novel technology would lead to an increase in project success. The qualitative results showed that DIYbio projects often apply technologies in a different way than academia and industry, rather than success being dependent on novelty of the technology. In later stages, DIYbio projects actually contribute to the development of technologies, as seen with PCR and digital microfluidics. The quantitative results show no significant relation between technological novelty and project success. Hypothesis 2 is therefore rejected.

Hypothesis 3 stated that a moderate market size would lead to an increase in project success. The qualitative and quantitative results indicated that projects have different target groups which are both different in scope and size, e.g. there were local or DIYbio community projects which were aimed at 20 to 10,000 people and global projects aimed at 1000 to millions of people. Furthermore, quantitative results showed that the target market of a project becomes more clear over time. The regression analysis shows that there is no relation between intended target market and project success. H3 is therefore rejected.

Hypothesis 4 stated that a competent project leader would increase the success of a project. The qualitative results helped in describing what a competent leader entails in a DIYbio project: a servant and enabling leader with real authority, experience and a network in the early stages, and a leader with formal authority to adhere to regulations and acquire funding in the later stages. The quantitative results did not show a significant relationship between a competent project leader and project success; H4 is therefore rejected. The quantitative results did, however, show a significant negative relationship between an incompetent project leader and project success.

Hypothesis 5 stated that a higher degree of variety in knowledge and skills would lead to an increase in project success. The qualitative results show that interviewees agreed that a higher diversity in backgrounds was helpful to a project and this showed in both labs and a startup program. The quantitative results also showed a significant weak positive correlation between knowledge diversity and project success. Hypothesis 5 is therefore accepted, with the disclaimer that the relation is weak in terms of quantitative results but supported by qualitative data.

Hypothesis 6 stated that an increase in funding would lead to an increase in project success. However, the qualitative results quickly showed that the strength of DIYbio is in making the most of few resources, and that substantial funding becomes important when trying to found a startup. The qualitative results show no relation whatsoever between funding and project success, H6 is therefore rejected.

Conclusion

The aim of this research was to how and why the DIYbio community influences DIYbio project characteristics and to find out which characteristics of a DIYbio project influenced its success. To do so, two research questions were formulated. The first research question was:

What is the influence of the DIYbio community on DIYbio project characteristics?

Getting involved in the community often starts with a dissatisfaction with one's current or future job and a degree of rebelliousness against society. People then start to seek and meet up with like-minded people. When meetings with these people become more frequent, a lab is needed to experiment together. People have an entrepreneurial mindset, both in finding or building a lab and developing ideas created in a lab. In the US, this is mainly a commercial mindset, with lots of funding being available, allowing the community to continuously grow. Part of the funding comes from government institutions which allows a level of control over what is done in the community. In Europe, people started out without pre-constructed commercial ideas, but after a successful wave of European biohackers the next generation is small and has adopted the commercial mindset from the beginning. In Africa, South America and Asia the community is up and coming and is driven by national problems to which DIYbio could be a solution. There is also a divide between technologists who tinker with and develop technologies and bio artists who use synthetic biology to invoke ethical discussions concerning genetic engineering. All in all, a DIYbiologists position in the community influences whether a project is a fun experiment, a technological advancement, an artistic expression or a commercial endeavor. Within these different directions for a project, different relationships with the characteristics defined in this research were found. The second research question was:

Which project characteristics determine the success of DIYbio projects?

The quantitative results only prove a relationship between knowledge diversity and project success, but the qualitative results allow more insights into what contributes to DIYbio project success. Acquiring lab funding and equipment is an important driver in the discovery stage. DIY biologists typically start experimenting without clear purpose, using existing technologies for different applications than academia or industry, adhering to standard lab protocols. In the development phase, an idea shows potential and a project team wants to develop it further, the purpose of the project becomes more clear along with the intended target market. The technology itself can then be developed further while adhering to or creating new regulations. Successful projects are then diffused and often try to give back to the community in the form of open source designs or knowledge sharing, which in turn gives technologists the opportunity to further develop the technologies and provide support for new experiments. Also, successful projects provide inspiration and technological opportunities for bio artists, who in turn provide inspiration for new experiments. Altogether, regulation, technology, market, leadership, knowledge diversity and funding all influence project success but the relationships are more complex than inverse U-shaped or positive linear relationships.

Discussion

Research quality

The quality of this research was dependent on its reliability and validity (Bryman, 2016). The reliability of this research concerns its repeatability (Bryman, 2016). The repeatability of this research consists of three parts: data collection, data analysis and interpretation of results. Since the data collection is highly dependent on other parties, namely the interviewees and respondents of the survey, there is a low chance that the same amount of interviewees and respondents can be reached if this research is repeated. The data analysis consists of two parts. The qualitative part consisted of open coding which was heavily subjective because of the interpretation and classification of the researcher. The quantitative part entails a regression analysis in R, which is highly codifiable and therefore also repeatable, even with a different data collection. To ensure quantitative repeatability, all R code is included in Appendix G of this research. For the interpretation of the qualitative results, it is not possible to let another person look at the same data and reach the exact similar conclusions, since the narrative constructed in the results chapter is based on the interpretations of the researcher. For the interpretation of the quantitative results, hypotheses were only accepted when there was a clear and significant ($p < 0,05$) effect; any other significant results were interpreted in the same manner. Also, model quality analyses were performed to ensure that the results were robust (Bryman, 2016). All in all, the repeatability and consequently the reliability of this research is low for the qualitative analysis and high for the quantitative analysis.

The validity of this research concerns the external validity and construct validity (Bryman, 2016). Since this research is performed by one researcher, internal validity is not applicable. The external validity entails the generalizability of the research. Whether the research is generalizable to the entire DIYbio community is highly dependent on the number of interviewees and respondents. For the qualitative results, the 9 interviewees of this research seem to be a representative group for the entire DIYbio community, at least for the topics discussed in this research. For the quantitative results, the 32 complete responses are not sufficient to give a clear overview of the community since projects differed too greatly within the 32 responses. In terms of construct validity, this research does not cover all possible factors that could contribute to the success of projects. Based on the theoretical framework presented in Chapter 2 this research does cover highly important factors of project success in biotechnology projects. The quantitative results do not offer satisfactory conclusions on the validity of the 6 variables chosen for this research, as only one hypothesis can be accepted. However, the qualitative results do offer explanations about the nature of the relationships between the independent variables and project success, meaning that the hypotheses rather than the variables itself might not have been well-constructed. Altogether, the validity of this research is quite low.

Limitations

First of all, the nature and size of the DIYbio community was hard to determine beforehand, as well as the right people to talk to. When using Google to search for information about DIYbio, the top hits are all related to the DIYbio community run by MIT. It was therefore quite surprising that the majority of the interviewees said they did not associate with this group. It took quite a while before seeing the (subtle) differences between parts of the world, technology and bio art, all the different labs and their business models and all organizations that are part of DIYbio. Since the community was so widespread, there were no standardized communication channels to reach the community. It took time to gain legitimacy in the communication that did exist such as the Facebook group or Slack channels.

For the qualitative part of this research, two limitations stood out. First, the DIYbio group consists of different types of people. Speaking to community founders/leaders, startup founders, lab founders and an iGEM competitor from the US, Europe and other continents was satisfactory, although speaking to a bio artist would have been a useful addition. Despite focusing on bio artists in the last round of approaching interviewees, only one replied that she was interested but could not make time in the weeks after, especially due to being located in the west of the US. The second limitation was to weigh the opinions of the interviewees about the MIT DIYbio community. On the one hand there was the degree of control of the US government, also touched upon in the results, that was clearly holding back some of the interviewees from speaking freely because they indirectly received funding. On the other hand, people who were absolutely against the MIT DIYbio community sometimes made accusations that approached conspiracy theories and slander. The researcher thinks that the right weights were applied to the statements of all interviewees.

In terms of quantitative results, the combination of characteristics from industry (regulation, technology, market) and projects (leadership, funding and knowledge diversity) was quite logical, but forming hypotheses proved difficult since it was unclear what projects existed and how they were embedded in the community. The great diversity in projects, from beer to cancer and from technology to art, also made it hard to make predictions about the entirety of projects. Despite the exact predictions being wrong, all variables included in the research turned out to be relevant for the community and projects and together the results about the variables allowed a coherent story to be written. The main limitation is the low response rate on the survey. This can be partly explained by the lack of communication channels and legitimacy in the community explained before. On top of this, respondents indicated that not all questions were applicable to their project, it was hard to circumvent this as projects differed greatly. To counter these limitations, the researcher tried to post the survey in as many channels as possible, becoming a member of multiple communities and interacting with community members in Slack, Facebook, Reddit and independent channels and forums. Also, over 100 people were contacted personally, as well as 561 iGEM teams. Community leaders were not willing to distribute the survey themselves, but did allow the researcher to use their name to gain legitimacy. Also, the survey was adjusted slightly to make the questions as inclusive as possible to all types of projects. All in all, the researcher is satisfied with the effort put in spreading the survey, but not with the response rate of 32.

If more survey responses (~100) would have been obtained, this research would have been entirely quantitative. While this would have been more interesting in terms of looking at causal relationships between the independent variables and project success, the qualitative data added a richness to the information about the community and project success that would have been missed otherwise. The aim was never to do entirely qualitative research, but if this would have been the case it would have been interesting to speak to bio artists and pure technologists. Altogether, the researcher is satisfied with the combination of quantitative and qualitative results.

Theoretical implications

As explained in Chapter 1, user communities literature often uses Open Source Software (OSS) communities for empirical research; this study focuses on the DIYbio community. Similarities and differences between these communities help to further develop user communities theory. Martinez-Torres & Diaz-Fernandez (2014) identify the 8 most studied topics in relation to OSS. *Table 9* below compares these 8 topics between OSS and DIYbio (Martinez-Torres & Diaz-Fernandez, 2014).

Table 9. Literature comparison between OSS and DIYbio.

Topic	**OSS**	**DIYbio**
Collective intelligence	- Interaction and collaboration is a powerful driver - Majority of participants contribute to satisfy personal goals - Corporate collective intelligence is an asset	- Interaction and collaboration are important drivers in discovery phase - Experimentation starts from personal interests - Once a promising project is found, it is first commercialized and then knowledge diffuses back into the community, excluding open source technologists
Structure of communities	Key group is core developers, periphery is motivated by core developers	Labs and individuals operate independently and cooperate based on personal networks MIT tries to steer the direction of the community with a franchise model of tying labs to their name by giving subsidies; a large part of the community does not associate with this.
Success	Organizational factors Software quality Community service quality	**Discovery** Different applications of existing technologies Basic lab protocols Lab funding and equipment Free experimentation without clear purpose **Development** Develop technologies Use community and network for diverse knowledge base **Diffusion** Compliance to regulation or introduce new regulation Venture capital Giving back to community
Virtual organizations	Shared goal or interests Geographical distribution Use of ICT to communicate	Shared general goals/interests, different specific content-related goals/interests Geographical distribution Physical and digital communication
Motivation	Developer: Altruism,	DIY biologist: Dissatisfaction

	reputation User: ease of use, price, autonomy	with job, activism
Shared knowledge	Altruism Identification Reciprocity Shared language	Giving back to community DIY kits Personal networks Conferences
Learning	Social learning process	Social learning process, tacit knowledge
Innovation process	A highly structured series of stages that unfold over time: the generation of ideas and concepts; the design and engineering stage and test and launch stage	Stages: Free experimentation without purpose or structure, developing a product while focus is applied, diffusion through revealing or commercialization.

Practical implications

On top of the contributions to user communities literature, this research has implications for the DIYbio community and society. First of all, the qualitative results highlight the similarities and differences in the community, which provide a first step in identifying the motivations for people to engage in DIYbio in some way. The aspects of being activistic, dissatisfied with one's current job and being entrepreneurial can be promoted by communities to attract more people. Identifying these aspects can also help people who have these characteristics approach communities themselves. Furthermore, the DIYbio project cycle can help communities to place their current projects in perspective and the activities can help project members and leaders decide what to focus on in managing their projects. The quantitative results show that project teams should try to include a diverse pool of people in their project to increase project success.

This research has also shown that DIYbio is a user community with positive impact on society. The resourcefulness and creativity in the community allows technologies to be applied in unique ways and the vast technological knowledge helps the further development of relevant technologies for healthcare. Also, bio art contributes to the public debate on genetic manipulation. With the rising costs of healthcare and medicine development, this research shows that DIYbio actively engages in making equipment and materials more affordable. The democratization of synthetic biology also helps to tackle both the rising complexity of scientific research and the social challenges that are paired with technological challenges. Integrating DIYbio in current innovation systems is difficult, because this research also shows that the strength of the community is in independent experimentation without an agenda. However, pharmaceutical firms, governments and/or venture capitalists could contribute by funding projects that show potential under two conditions: not interfering in the experimentation without a purpose phase and allowing (part of) the knowledge generated in the project to freely be transferred back to the community when a project is successful.

Further research

During the course of this research, multiple people in the community have indicated needs for further research. The first was mentioned in the results section, which is the need to make a framework for quantification of DIYbio labs. The framework would include what dimensions to measure such as reach, education and experimentation. Specific indicators would have to be picked for the different dimensions, such as amount of youth reached, amount of volunteers and number of successful projects or startups. The second direction for research was brought up in a conversation with a lab founder who did not want to be interviewed. However, this person proposed to research the social and emotional barriers that were present when deciding whether or not to engage in the DIYbio community. This would be an interesting topic for open source communities/citizen science research.

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Appendix A. Interview guide

Do you give permission for the sound of this meeting to be recorded?

Introductions

Can you explain how the DIYbio community works and you personal history in DIYbio?

Questions based on survey response/comments: different per interviewee

Questions based on survey:
Do you have…

…Any other comments on technologies (maturity of technologies) used in DIYbio?

…Any other comments on the market variable?

…Any other comments on regulation?

…Any other comments on leadership?

…Any other comments on funding?

…Any other comments on knowledge diversity?

Thank you for your time, do you have any other remarks regarding my research?

Appendix B: List of people, groups and startups contacted for interviews and survey response

Who	Type
DIYbio Facebook	Group
Biosummit 5.0 Slack	Group
DIYbio gmail group	Group
Hackteria forum	Group
BioCurious mailing list	Group
CounterCulture mailing list	Group
DIYbio subreddit	Group
Biohackers subreddit	Group
JOGL slack	Group
David Kong	Individual
Esther Kim	Individual
Chris Schulz	Individual
ChiTownBio	Group
Carolyn Angleton	Group
BioClub Tokyo	Group
FabLab Lima	Group
Hive Bio Lab	Group
Brico Bio	Group
Habitat Lunares	Group
BUGSS	Group
Nutshell Biohub	Group
Rudiger Trojok	individual
Digi Bio	Group
Urs Gaudenz	Individual
Thomas Landrain	Individual
Chan'nel Vestergaard	Group
Biotech without borders	Group
Allbiotech	Group
Bongo Tech & Research labs	Group
Xinampa	Group

Wizkit	Group
Olatunbosun Obayomi	Group
Victoria Makerspace	Group
Lucas Potter	Group
Bioblaze community bio lab	Group
Sarah Blossom Ware	Individual
iGEM	Group
Mycology for architecture	Group
Amino Biolabs	Group
Open Insulin Foundation	Group
Sound Bio	Group
Vitroplantae	Group
Free radicals	Group
Nemeton	Group
Bangladesh Biotechnology Olympiad	Group
Biohack Philly	Group
Bridge biofoundry foundation	Group
FabLab Hamamatsu	Group
Yealthy	Group
Yuan Xue	Individual
BioLaunch	Group
Champaign-Urbana FabLab	Group
DreamSpace Academy	Group
starlabs bangladesh	group
Kilobaser / Alex Murer	Startup
SwissDeCode / Gianpaolo Rando	Startup
Nordetect / Keenan Pinto	Startup
Hackerium	Group
BosLab	Group
JOGL	Group
Augmentation limitless	group
FabLab UPSaclay	Group

London biohackspace	Group
RÿSteam CPH	Group
BioLogik Labs	Group
Benzyme Ventures	Group
YCAM	group
HBBE	Group
Open science network	Group
Scyfup	Startup
Bacto crop	Startup
Synbio Brasil	Group
biohacking space peshawar	Group
Nature Lab	Group
Brilliant Labs	Group
Biotec Latina	Group
Bio-UTEC	Group
2fd5	Group
Smallhold	Startup
Tele Agri Culture	Startup
Martin Asser Hansen for BioPieces	Group
Minicircle	Group
nona software	Group
Edible Makerspace Singapore	Group
Nation of makers	Group
Biook	Group
Tellus Technologies	Group
ReaGent	Group
Accessible Genomics	Group
AI@EDGE	group
Nucleate	group
OpenCell	Group
Experiment Foundation	Group
Seeding Labs	group
Bento Lab	group

Froth technologies	group
Spira Inc	Group
OpenTrons	group
Mirela Alistar	Individual
Alessandro Volpato	Individual

Appendix C: Survey questions

Introduction	Dear community member, Thank you so much for taking the time to fill in this survey! The main objective of this survey is to explore the characteristics of a DIYbio project. Secondly, we are interested in the possible positive effect of being part of the DIYbio community. Before starting the survey we would like to ask you to think of **one specific** DIYbio project in which you are/have been involved in, preferably in the area of healthcare. A project is delineated to the discovery, development and diffusion of one product. Some questions concern placing your project on a scale, please do not hesitate to use the full spectrum of values. The survey is completely anonymous. It is possible to fill in your contact details at the end of the survey in order to receive results of the research. We intend to present the results at the next Global Community Biosummit. The survey will take approximately 10 minutes to fill in. You can now continue to the next section.	
General	Please give a short description of the project you have in mind. You can be as specific in sharing details as you feel comfortable with. > Text box	
	When did the project start? > Date	
	When did the project end? If the project is ongoing, please fill in the expected end date. If this is not clear yet you can continue to the next question. > Date	
Project goals	Were specific goals set for the project? > Yes	Were specific goals set for the project? >No
> Split	What were the goals of the project? > Text	What was the original need or purpose that led to the initiation of this project? > Text
	To what extent have the project goals been reached? > Scale 0-100	To what extent do you feel like this need or purpose has been fulfilled? > Scale 0-100

	To what extent are you satisfied with the outcomes of the project? > Scale 0-100	To what extent are you satisfied with the outcomes of the project? > Scale 0-100
	To what extent are you satisfied with the process of the project? > Scale 0-100	To what extent are you satisfied with the process of the project? > Scale 0-100
Project characteristics		
Technology	What is the main (bio)technology that is used in the project? > Text	
	TRL	We are interested in the novelty of the technology used in your project. A systemic measure for technological maturity is the Technological Readiness Level (TRL). The scale is displayed below. *TRL scale* On the following scale, please indicate the Technological Readiness Level you deem to be most applicable to your project. > Scale 1-9
	Community	To what extent do you feel like the DIYbio community has enabled you to use a more novel technology? (0-100)
Market	What is the intended target group or market of your product? > Text What is the intended size of this market (approximately)? > Text: value	
	Market size category	Please pick the scale of the market you **intend to capture** which fits your project best. > Category 1-4
	Community	To what extent do you feel like the DIYbio community helps in reaching your

		intended market? (0-100)
Regulation	Depending on the technology and market, different types and intensities of regulations are encountered. For example, a newer technology can be associated with higher amounts of uncertainty and can therefore be strictly regulated or a product developed for an (inter)national market has to comply with a lot of guidelines. What role does regulation play in your project? > Text	
	Regulatory density	To what extent does the product developed in your project have to adhere to obligatory standards, measures and procedures relative to other products you know of? (Think of clinical studies, certain procedures to ensure the safe use of a medicinal product or administrative requirements/regulations for the appropriate manufacturing and safe handling of medicines, market authorization, etc.) > Scale 0-100
	Uncertainty and risk	It can sometimes feel like the amount of regulations does not correspond to the amount of uncertainty and risk that is associated with the product. This uncertainty can be caused by complexity of the product, process and patient targeted by the product, for example highly complicated molecular structures and sophisticated manufacturing processes in gene-editing technologies. To what extent is the product developed in your project associated with uncertainty and risk relative to other products you know of? > Scale 0-100
	Community	To what extent do you feel like the DIYbio community

		has helped in identifying both the risks and the regulatory requirements of your project? > Scale 0-100
Project conditions		
	We are interested in the way your project is built up in terms of team size, diversity of backgrounds, leadership style and funding. How did the project team form? > Text How many people are involved in your project? > Value How many people from different backgrounds are involved in your project? (For example: a biological engineer, chemist, pharmaceutical regulation expert and a patient results in a score of 4 backgrounds) > Value To what extent do you feel like the DIYbio community has helped you in bringing together people with different backgrounds? > Scale 0-100	
Presence of project leader	Could you describe the leadership of the project and how decisions are made in the project? > Text	
	Decision-making authority category	Please indicate the type of decision-making authority which fits your project best > Category 1-4
	Community	To what extent do you feel like the DIYbio community has helped in finding the right leadership style for the project? > Scale 0-100
Amount of funding	Funding	How is/was the project financed? > Text How much funding has your project received (in US dollars)? > Value From how many different

		sources? > Value
	Community	To what extent do you feel like the DIYbio community has helped in acquiring funding for the project? > Scale 0-100
End	Thanks for participating in this survey. If you have any additional remarks you can leave them here: > Text If you would like to receive an overview of the results of this survey, please leave your email address below: > Text for email address	

Appendix D: Technology Readiness Levels

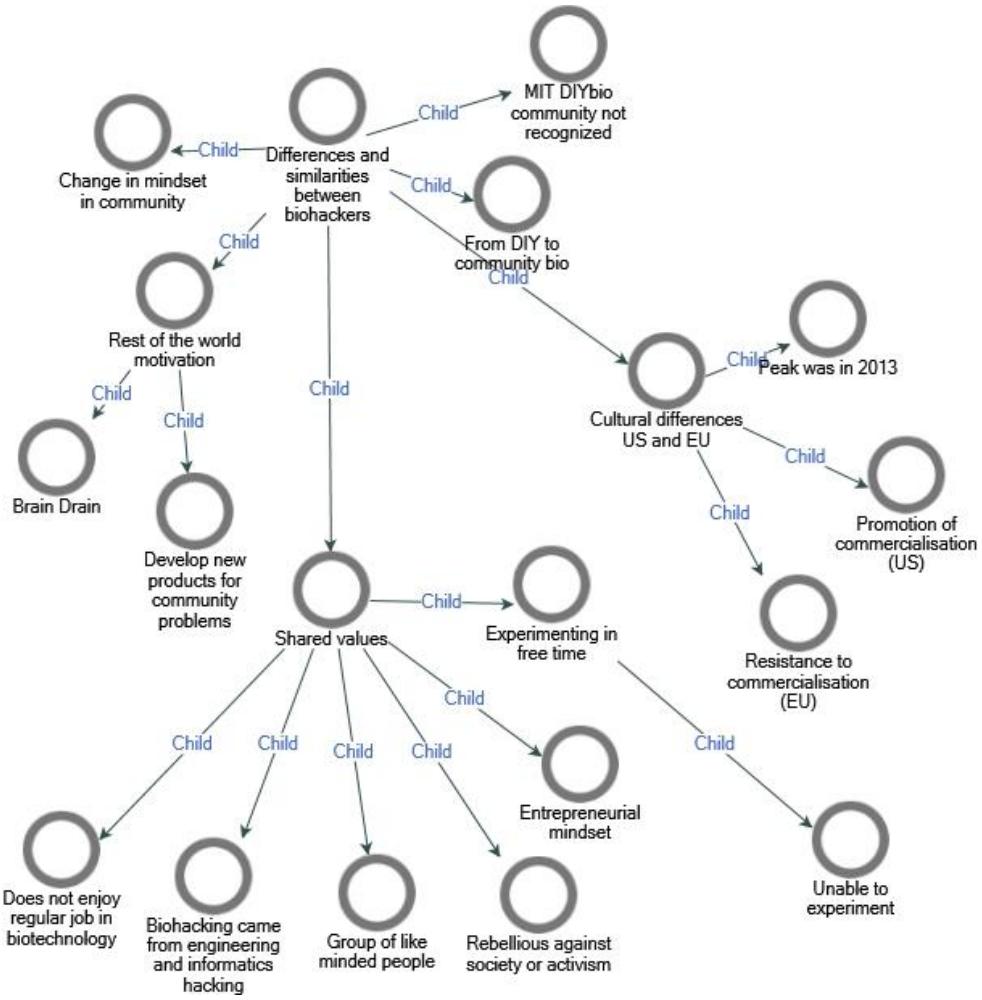
These are the 9 levels of the TRL framework, as derived from Héder (2017).

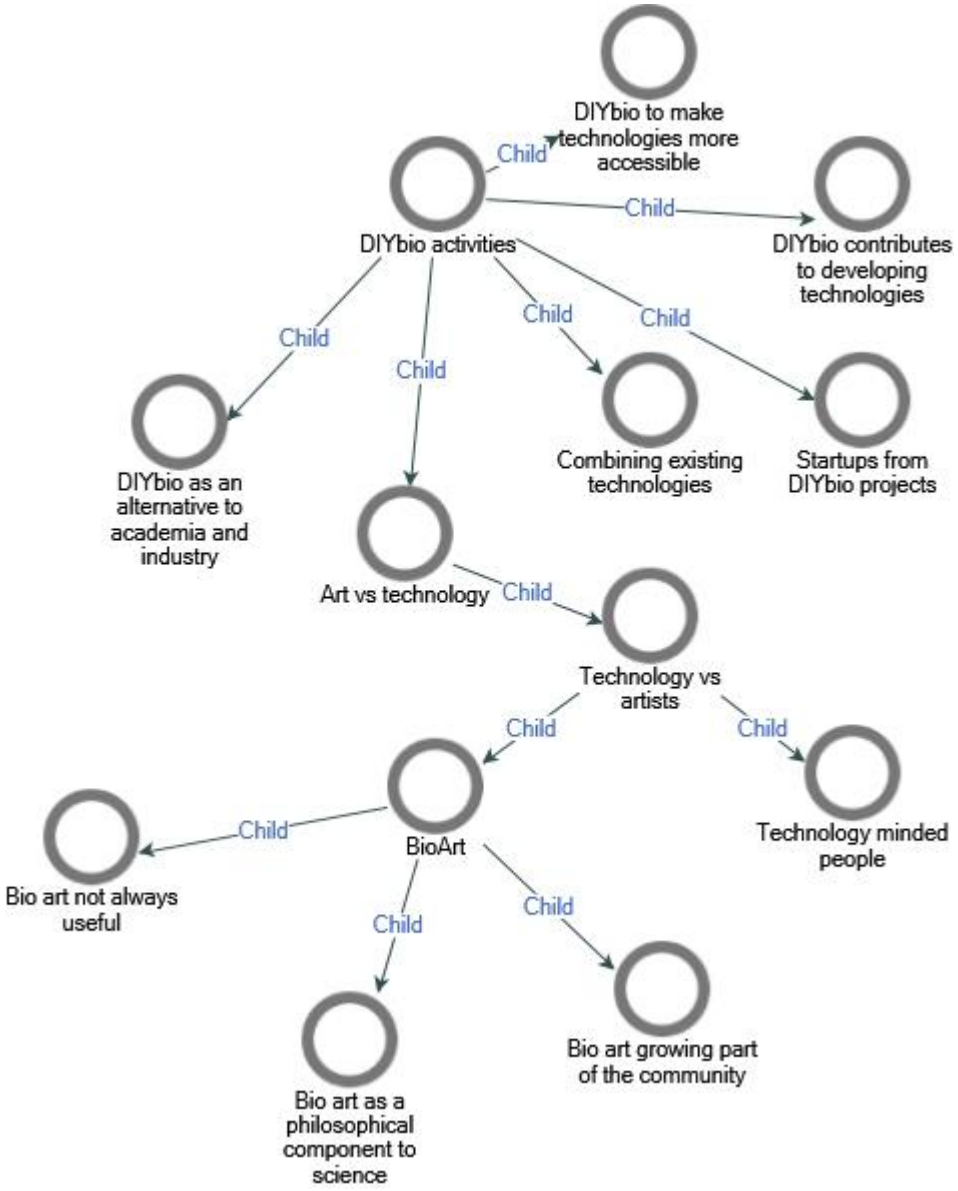
TRL 1 – basic principles observed
TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept
TRL 4 – technology validated in laboratory
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 – technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 – actual system proven in an operational environment (competitive manufacturing in the case of key enabling technologies or in space)

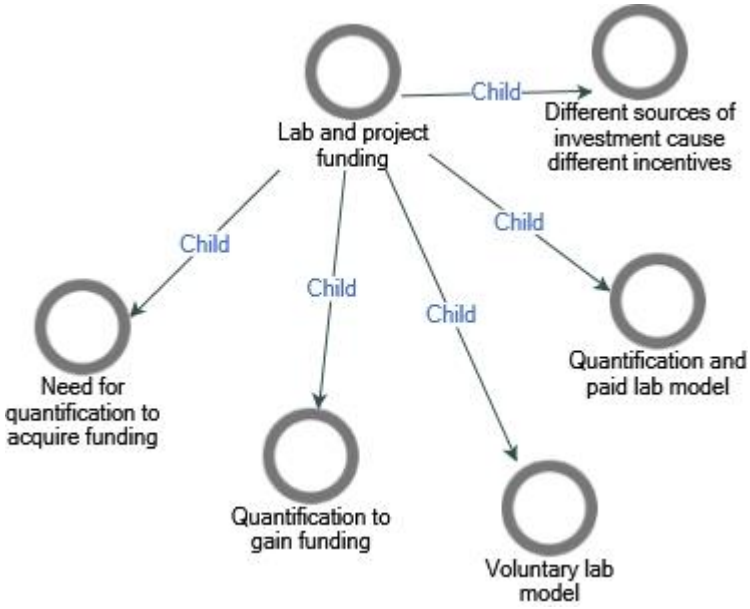
Appendix E. List of interviewees

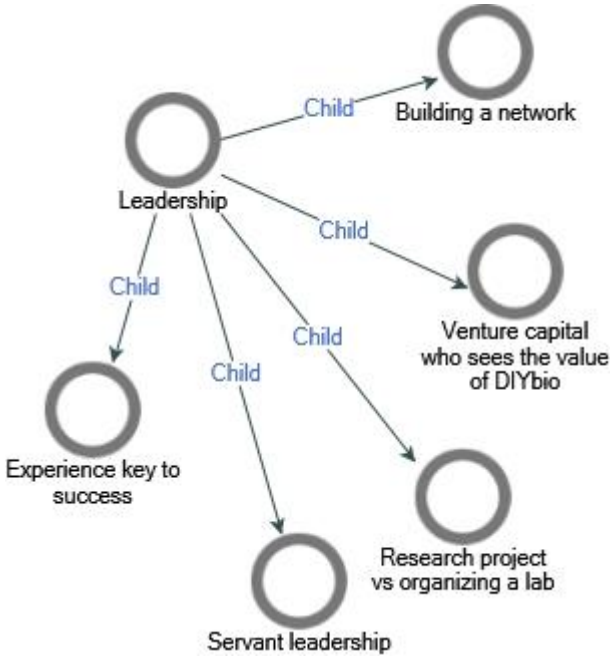
Interview	**Description**
1	Community founder
2	Early biohacker, lab founder
3	Community founder, lab founder
4	Early biohacker, lab founder, startup founder
5	Developing country lab founder, community leader
6	Lab founder
7	Early biohacker, lab founder, startup founder
8	Biohacker
9	Developing country iGEM competitor

Appendix F. Code trees of the four main categories of codes




DIYbio to make technologies more accessible
Child
DIYbio activities
Child
DIYbio contributes to developing technologies
Child
Child
Child
Child
DIYbio as an alternative to academia and industry
Combining existing technologies
Startups from DIYbio projects
Art vs technology
Child
Technology vs artists
Child
Child
Child
BioArt
Technology minded people
Bio art not always useful
Child
Child
Child
Bio art as a philosophical component to science
Bio art growing part of the community





Appendix G. *R* Code

```
setwd("~/UU/masterthesis")
alldata <- read.csv("diybio5.csv")

library(dplyr)
library(stargazer)
library(extraoperators)
library(ggcorrplot)
library(ggplot2)
library(car)
library(lmtest)
#---- transforming variables
```

```
#success variable
alldata <- as.data.frame(alldata)
alldata$Eff <- alldata$Eff/100
alldata$SatOut <- alldata$SatOut/100
alldata$SatPro <- alldata$SatPro/100
alldata$suc <- (alldata$Eff + ((alldata$SatOut + alldata$SatPro)/2))/2


#splitting TRL into novel technology (1-4) and mature technology (5-9)
alldata$TRL <- as.integer(alldata$TRL)
alldata[alldata$TRL <= 4,]$TRL <- 1
alldata[alldata$TRL >= 5,]$TRL <- 0

#transform market categories
alldata$Market <- match(alldata$Market, c("Individual or project team use", "Local or DIYbio
community", "National market", "Global market"))

#transform leadership categories
alldata$Leader <- match(alldata$Leader , c("There is no single leader with decision-making
authority; decisions are made with the entire project team", "There is no single leader with
decision-making authority; decisions are made with a leadership team", "There is a single
leader with decision-making authority but he/she is not competent", "There is a single
competent leader with decision-making authority"))

#scaling funding
alldata$FunLog <- log(alldata$Fun +1)

#calculating regulatory density
alldata$Reg <- alldata$Reg / 100
alldata$Risk <- alldata$Risk / 100
alldata$RegDen <- (alldata$Reg - alldata$Risk)
alldata$RegDen2 <- alldata$RegDen
alldata[alldata$RegDen > 0.1, ]$RegDen <- 3
alldata[alldata$RegDen < -0.1, ]$RegDen <- 4
alldata[alldata$RegDen %gel% c(-0.1,-0.05), ]$RegDen <- 2
alldata[alldata$RegDen %gle% c(0.05,0.1), ]$RegDen <- 2
alldata[alldata$RegDen %gele% c(-0.05,0.05), ]$RegDen <- 1


datadiybio <- data.frame(alldata$suc,alldata$TRL, alldata$Market, alldata$RegDen,
alldata$FunLog, alldata$Leader, alldata$Blau)
names(datadiybio) <- c("suc","TRL", "Market", "RegDen", "FunLog", "Leader", "Blau")
datadiybio$Market <- factor(datadiybio$Market , c(1,2,3,4))
datadiybio$RegDen <- factor(datadiybio$RegDen , c(1,2,3,4))
datadiybio$Leader <- factor(datadiybio$Leader , c(1,2,3,4))
datadiybio$TRL <- factor(datadiybio$TRL , c(0,1))
datadiybio <- as.data.frame(datadiybio)

#----
#correlation matrix and descriptives
model.matrix(~0+., data=datadiybio) %>%
  cor(use="pairwise.complete.obs") %>%
  ggcorrplot(show.diag = T, type="lower", lab=TRUE, lab_size=2, insig="blank")
summary(datadiybio)
```

```
#----
#OLS regression analysis
suctech <- lm(suc ~ TRL, data=datadiybio)
summary(suctech)
sucmar <- lm(suc ~ Market, data=datadiybio)
summary(sucmar)
sucreg <- lm(suc ~ RegDen, data=datadiybio)
summary (sucreg)
sucfun <- lm(suc ~ FunLog, data=datadiybio)
summary (sucfun)
suckno <- lm(suc ~Blau , data=datadiybio)
summary(suckno)
suclead <- lm(suc~Leader, data=datadiybio)
summary (suclead)

model1 <- lm(suc ~ RegDen +  Leader , data=datadiybio)
summary (model1)
model2 <- lm(suc ~ RegDen +  Leader + Blau , data=datadiybio)
summary(model2)
model3 <- lm(suc~Leader + Blau, data=datadiybio)
summary(model3)
model4 <- lm(suc~RegDen+Blau, data=datadiybio)
summary(model4)

suctest <- lm(suc~MarketSize, data = datadiybio)
summary(suctest)

stargazer(sucreg, type = "html", dep.var.labels = "Project Success", title = "Regulatory
density and project success", covariate.labels = c("Regulatory equilibrium", "Regulation is a
barrier", "Existing regulation is not sufficient"))
stargazer(sucmar, type = "html",dep.var.labels = "Project Success",title= "Market category
and project success", covariate.labels = c("Local or DIYbio community", "National market",
"Global market"))
stargazer(suctech, type = "html",dep.var.labels = "Project Success",title = "Technological
novelty and project success", covariate.labels ="Mature technology")
stargazer(sucfun, type = "html",dep.var.labels = "Project Success",title="Funding and project
success", covariate.labels ="Funding")
stargazer(suckno, type = "html",dep.var.labels = "Project Success",title= "Knowledge
diversity and project success", covariate.labels ="Knowledge diversity")
stargazer(suclead, type = "html",dep.var.labels = "Project Success",title = "Leadership style
and project success", covariate.labels =c("Leadership team", "Incompetent leader",
"Competent leader"))
stargazer(model1, type = "html",dep.var.labels = "Project Success",title= "Model 1",
covariate.labels =c("Regulatory equilibrium", "Regulation is a barrier", "Existing regulation is
not sufficient","Leadership team", "Incompetent leader", "Competent leader"))
stargazer(model2, type = "html",dep.var.labels = "Project Success",title = "Model 2",
covariate.labels =c("Regulatory equilibrium", "Regulation is a barrier", "Existing regulation is
not sufficient","Leadership team", "Incompetent leader", "Competent leader", "Knowledge
diversity"))

stargazer(sucreg,sucmar,suctech,sucfun,suckno,suclead, title= "Regression results",
align=TRUE, type = "html",dep.var.labels = "Project Success",covariate.labels =
c("Regulatory equilibrium", "Regulation is a barrier", "Existing regulation is not
sufficient","Local or DIYbio community", "National market", "Global market","Mature
```

```
technology","Funding","Knowledge diversity","Leadership team", "Incompetent leader",
"Competent leader") )
stargazer(model1, model2, type = "html", dep.var.labels = "Project Success", title =
"Regression models", covariate.labels =c("Regulatory equilibrium", "Regulation is a barrier",
"Existing regulation is not sufficient","Leadership team", "Incompetent leader", "Competent
leader", "Knowledge diversity"))

#checking for outliers, multicollinearity and heteroscedasticity
qqPlot(datadiybio$FunLog)
qqPlot(datadiybio$suc)
qqPlot(datadiybio$Blau)
vif(model1)
vif(model2)
bptest(model1)
bptest(model2)
```