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Drivers for the emergence of interdisciplinary knowledge areas: An actor-level perspective on building legitimacy for the case of synthetic life sciences

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ABSTRACT

No one discipline or knowledge area can spur the rise of novel technologies and solutions pivotal to mitigate the grand challenges confronting society. Such solutions increasingly require broad-based collaborations, new spaces for knowledge creation, and the emergence of interdisciplinary knowledge areas (IKAs). Little is known about the drivers for IKA emergence, specifically how their legitimacy can be built. Drawing on knowledge of emerging innovation ecosystems, we conceive legitimacy in terms of the need to align the views, skills, and motivations of diverse actors – between academia and industry and across disciplines as well. This exploratory study employs the mixed-methods approach of group concept mapping to examine drivers of new IKAs and specifically how legitimacy can be fostered from an actor-level perspective. This approach entails a series of steps whereby discussion is facilitated around a focus prompt, ideas are generated, the resulting statements are sorted (by participants) into categories and rated (for importance and changeability), and then analyzed and described using visual outputs. Employing synthetic life sciences as a case, an actor-based perspective is first provided of the drivers seen as most important and changeable, and how this varies by type of actor. We thereby elucidate initiatives promoting the emergence of IKAs, by stressing the importance of key actors or engaging with public concerns. Second, by examining similarities across actors, areas of consensus are highlighted, outlining a guiding vision to align their interests and goals. Third, by examining universities as a form of interdisciplinary invention ecosystem, we illustrate how universities are meaningful not only as a locus for groundbreaking research but a space where actors can collaborate for knowledge creation and exchange. Engaging universities through this lens, we finally provide a discussion of initiatives (outlined as propositions) that can promote the establishment of invention ecosystems, particularly around legitimacy-building by promoting broad-based collaboration.

1. Introduction

Interdisciplinary knowledge areas (IKA) provide the foundation for tackling grand challenges for society including the transition to renewable energies and the development and deployment of new solutions through technological, environmental and social innovation (Haas and Ham, 2015; D'Este et al., 2019; Rothe et al., 2020; Block et al., 2021; Sarpong et al., 2022). We here conceive of IKAs in terms of the combination of previously disparate fields of expertise, technologies, knowledge, and modes of understanding (Borge and Bröring, 2020). Through such combination and recombination of knowledge and expertise, novel spaces and opportunities emerge for addressing the solutions to the grand challenges confronting society – helpfully, these news spaces also orient the decisions of firms and research institutions of where and when to invest resources as well as for policy makers aiming to guide regulation and funding activities (Dattée et al., 2018).

Emerging technologies as such are the subject of substantial research (Daim et al., 2006; Rotolo et al., 2015; Zamani et al., 2022) and emerging interdisciplinary science fields have attracted growing attention (Baaden et al., 2024). To understand what drives the emergence of IKA, however, it is not sufficient to consider the technologies (and fields of science) involved. Rather, gathering insights into the mechanisms and

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processes underlying IKA emergence must highlight the importance of industries, markets, regulatory frameworks, and much else (Borge and Bröring, 2017). Moreover, advancing the current understanding of the emergence of IKA appears highly relevant to the body of research on collaborative research and knowledge creation (Bozeman and Gaughan, 2007; Gilain et al., 2022; Giannopoulou et al., 2019; Perkmann et al., 2021). As an example, the bioeconomy, as an IKA, encompasses diverse technologies, some novel and possibly radical (e.g. biotechnology), spans sectors such as agriculture, energy, and industry, might require the development of novel (bio-based) materials to substitute for fossil-based counterparts, creates a range of products with market potential, and poses potentially thorny regulatory issues, including the recycling and re-use of waste materials and by-products (Pietzsch, 2020; Fritsche and Rösch, 2020).

Despite their increasing relevance and impact, it is still unclear what drives the emergence of IKA and how this might be better facilitated (Rotolo et al., 2015). Given the importance of IKAs to tackle the grand challenges of society, and fostering the knowledge creation, which is the engine of social goods, there is a great need to better understand how they emerge and become established (Ledford, 2015). Such insights would be helpful for nurturing and catalyzing the creation of particular IKAs that are deemed to address specific grand challenges. In this regard, there is a need to better examine the conditions and processes of emergence. Even though legitimacy in particular emerges as key for overcoming the "liability of newness" (Thomas and Ritala, 2022, p. 518), existing literature is sparse on how exactly the aim of legitimacy takes shape for IKA. Legitimacy in this context can be conceptualized as "the social acceptability, plausibility, and credibility beyond [...] material resources and capabilities (Thomas and Ritala, 2022, p. 516, based on Suchman, 1995).

The lack of insights into legitimacy building of IKA results from the complexity, uncertainty, and dynamics which are inherent in such areas. Complexity stems from the confluence of formerly distant fields of knowledge that build the basis for the emergence of new IKA (Borge et al., 2022; Gruber et al., 2013; Maine et al., 2014). The confluence of technologies has in mind a more fixed target outcome: utilizing these new technologies to yield innovations. When it comes to knowledge areas, however, the outcomes are necessarily more open-ended – and the dynamics and processes less specified and understood. This fact is compounded for IKAs, most of all for those more distant from one another and lacking the muscle memory of working together (Kodama, 2019). To deal with this complexity and uncertainty, i.e. to integrate previously separated knowledge and sets of expertise, the dynamics between actors are key (Borge and Bröring, 2017; Rothaermel and Boeker, 2008; Nonaka and Toyama, 2003). Activities and interconnections on actor-level are driving developments on the level of whole IKA, aligning interests, motivations and visions of different actors (Nonaka et al., 2006; Barney and Felin, 2013; Foss and Lindenberg, 2013; Cunningham et al., 2018).

Drawing on this actor-based perspective, the innovation ecosystem metaphor proves useful. In specific, the notion of innovation ecosystems can highlight the co-evolutionary processes emerging through the interaction of different actors, often in symbiosis (Dedehayir et al., 2018), along with providing insights on the emergence of innovation ecosystems (Dedehayir and Seppänen, 2015; Dedehayir et al., 2022, Jacobides et al., 2018; Granstrand and Holgersson, 2020; Li-Ying et al., 2022). The lifecycle of an innovation ecosystem comprises four phases: birth, expansion, leadership, self-renewal (Moore, 1993). Ecosystem emergence is mostly located during the birth phase, covering the timeframe from scientific discovery or invention to commercialization (Moore, 1996). As a key point of overlap with our focus on IKA, Dedehayir et al. (2022), in their work on roles in innovation ecosystems, have illustrated how universities hold a central role for discovering, inventing and generating ideas in the very early stages of ecosystem emergence. Assuming the role as experts (or the locus of their activities), universities first and foremost generate knowledge, but also provide expertise for and transfer technology to other actors of the quadruple helix such as industry partners, the public and regulatory bodies (Dedehayir et al., 2018; Miller et al., 2018). It can thus be assumed that universities and other actors play a crucial role in driving emerging IKAs, but the question remains how their actions and interactions contribute to building legitimacy for new IKAs.

Accordingly, this study aims to identify drivers for the emergence of IKAs, and specifically how to build legitimacy around new IKAs, by developing and proposing strategies able to facilitate the alignment of the diverse interests, motivations and visions of actors across the emerging ecosystem. As an exemplar IKA, we utilize the case centering on a German university in the region of North-Rhine Westphalia that is in the process of re-branding itself around the "synthetic life sciences". Synthetic life sciences sit at the convergence of life sciences, computer sciences, engineering, and other formerly separate research streams, thus making the effective integration of interdisciplinary knowledge crucial to the emergence of this field (Sorenson et al., 2006; Gruber et al., 2013; Shapira et al., 2017; Trump et al., 2020). Discussions of synthetic life sciences are increasingly in the mainstream. Propelled by hallmark breakthroughs such as the creation of the first synthetic genome (Gibson et al., 2010) or use of metabolic engineering to produce the antimalarial drug *artemisinin* (Martin et al., 2003; Kung et al., 2018), there is greater recognition of the substantial promise and potential futures that these novel technologies support.

To center actors and their perspectives, we employ the mixed-methods approach of group concept mapping (Kane and Trochim, 2007; Kane and Rosas, 2018). This approach entails a series of steps whereby discussion is facilitated around a focus prompt, ideas are generated, the resulting statements are sorted into categories and rated (for importance and changeability) by participants, and then analyzed and described using visual outputs. By studying differences and similarities regarding perceptions and priorities across actors, we identify specific areas where coherence and consensus do exist. This enables us to develop propositions on where and how progress towards building legitimacy for new IKAs might be most feasible.

Through the insights of this case, this study advances the emerging body of knowledge on building legitimacy for innovation ecosystems and IKAs. We propose three mechanisms by which legitimacy can be fostered: (1) building *capabilities* that are required or missing, including through participation of specific actors; (2) resolving *obstacles* for deeper interdisciplinary collaboration or public acceptance to materialize; and (3) using prospective *selling points* to foster broader public or political acceptance. These insights signal the importance of universities (and their partners), as actors, and how these can contribute to developing *capabilities*, resolving *obstacles*, and turning *selling points* into a guiding vision to foster legitimacy building for emerging IKA.

Our findings also contribute to the academic engagement literature, specifically the understanding of spaces for collaborative research and knowledge creation (Bozeman and Gaughan, 2007; Gilain et al., 2022; Giannopoulou et al., 2019; Perkmann et al., 2021). Much of the extant literature around academic engagement has tended to focus on university-industry linkages or the role of new types of intermediary actors and organizations. In contrast, the present study provides insights on the drivers and initiatives able to promote legitimacy and alignment within ostensibly more traditional spaces, thereby facilitating recruitment of needed and missing expertise and knowledge into this IKA. It achieves this by, first, considering universities as invention ecosystems in the direct sense and, second, by demonstrating the utility of an actor-level perspective on emergence of IKA. On the second point, we propose that activities and interconnections at the actor level are driving developments on the level of whole IKA (Barney and Felin, 2013; Foss and Lindenberg, 2013; Cunningham et al., 2018).

2. Conceptual background: interdisciplinary knowledge areas and relevant roles from an innovation ecosystems perspective

To develop a conceptual framework for emergence in general and building legitimacy in particular, which can be leveraged in relation to IKA, we begin by considering how emergence has been generally applied to understand innovation ecosystems (for better readability, we use innovation ecosystem and ecosystem as synonyms in the following). While doing so, we will endeavor to highlight and clarify the role of universities and related actors. Emergence of innovation ecosystems has been examined, as a phenomenon, to better understand how legitimacy is being built to co-create value through the co-evolution of heterogeneous actors (e.g., research institutions, universities, firms, regulatory bodies) and their respective capabilities (Adner and Kapoor, 2010; Kapoor and Lee, 2013; Autio and Thomas, 2014; Moore, 1993; Ganco et al., 2019). While the actors involved do not cease to compete, there is a deeper sense where, as members of the same ecosystem, they are reliant on a common set of assets (e.g. technologies, knowledge, skills), and thus increasingly interdepend on activities and decisions of one another (e.g. Bogers and West, 2012; Ritala and Almpanopoulou, 2017; Ganco et al., 2019).

The innovation ecosystem literature also provides insights on the typical lifecycle, and thus the kinds of drivers that matter for their emergence. Moore (1993) specifies four stages (for innovation ecosystems): birth, expansion, leadership, and self-renewal. Given our focus on the emergence of IKAs, we focus on the birth phase, usually conceived as ranging from discovery of an opportunity or inventing a technology to its broader market availability (Pushpananthan and Elmquist, 2022). Ultimately, in this context, success in the birth phase is contingent on fostering an aligned understanding among relevant actors of the value of the focal invention (Moore, 1996). While literature on the ecosystem emergence is in its infancy, the work of Dedehayir et al. (2022) and Pushpananthan and Elmqvist (2022) offer an initial understanding of critical roles during ecosystem emergence.

Indeed, at the earliest stage in the lifecycle, universities exercise a key role for discovery, invention, and idea generation (Dedehayir et al., 2022). Within such ecosystems, universities' main role is to generate knowledge through basic and applied research and enable technology transfer (Bercovitz and Feldman, 2006; Hughes and Kitson, 2012; Schaeffer and Matt, 2016; Baglieri et al., 2018; Borge and Bröring, 2017, 2020; Zhao et al., 2020; Plantec et al., 2023). Actors at universities serve as a source of advice and expertise to others in the quadruple helix: industry partners, the public, and regulatory bodies (Dedehayir et al., 2018; Carayannis and Campbell, 2009; Miller et al., 2018; Zhang et al., 2019). Implicitly, there is a division of responsibilities at work: researchers at universities generate ideas and insights, while local firms are needed to get a sense of the commercialization potential – there are caveats depending on a range of individual, organizational, and institutional factors (Perkmann et al., 2013, 2021; Plantec et al., 2022, 2023).

We gain further insights on the roles of universities and academic actors by taking a closer look at how their relationships are conceived, notably with industry. In this vein, the academic engagement literature provides key insights by its focus, as defined by Perkmann et al. (2013), on "knowledge-related interactions of academic scientists with external organizations". There is recurring emphasis in this literature on the importance of academic-industry collaborations and other related activities for generating novel scientific knowledge (Perkmann et al., 2013, 2021; Plantec et al., 2022, 2023). Indeed, given that academic engagement positively impacts research productivity and tends to be undertaken by more successful scientists (Perkmann et al., 2021; Plantec et al., 2022, 2023), research in this vein contradicts arguments that an industry-focused orientation and academic excellence are incompatible. For instance, Plantec et al. (2023) illustrates how such an orientation, and the ability to collaborate with non-academic actors, delivers greatest impact for "user-inspired fundamental research", the rarest of the categories that they examine. D'Este et al. (2019, 2023) discerned an especially strong relationship between more interdisciplinary researchers and benefits in the form of technology transfer and scientific findings with greater visibility for policy, media, and society at large. What emerges is the sense that the skills and focus of interdisciplinary researchers could contribute more directly to society and its grand challenges than is typically assumed.

More broadly, the academic engagement literature has identified several key antecedents for such activities, focusing on a range of individual, organizational, and institutional factors (Perkmann et al., 2013, 2021). Typically, there is emphasis on the greater engagement by researchers from applied disciplines, such as engineering or computer sciences (Bozeman and Gaughan, 2007; Bekkers and Bodas Freitas, 2008; Martinelli et al., 2008; Perkmann et al., 2013). In contrast, those from the social sciences typically engage more through personal ties or labor mobility – though it is worth noting the situation seems to be shifting over time (Hughes and Kitson, 2012; Abreu and Grinevich, 2013; Perkmann et al., 2021). The understanding of organizational factors, in contrast, appears relatively underdeveloped – mostly there is a focus on the quality of the educational institution (Perkmann et al., 2013, 2021). One notable insight, however, is that the level of control exercised by a university can negatively impact the level of academic engagement (Halilem et al., 2017). Over time, there is also a growing appreciation of the positive influence of informal exchanges and ties, that is, among peers (Perkmann et al., 2021). To the extent universities are perceived to fall short (e.g., Feldman, 1994), there is thus an attempt to assess how they can better function as collaborative spaces for knowledge generation and innovation (Hayter, 2016; Castillo Holley and Watson, 2017; Chan et al., 2022). Often, this leads to calls for "novel organizational structures", e.g. research centers or technology transfer offices, that help reduce information asymmetries and promote collaboration (Bercovitz and Feldman, 2006; Bozeman and Gaughan, 2007; Perkmann et al., 2013; Zhao et al., 2020). Similarly, the creation of local university spin-offs is discussed, with emphasis on the local element, as another mode for universities to deliver active economic contributions and act as an incubator for entrepreneurial students or faculty (Breznitz and Feldman, 2012; Johnston and Huggins, 2018; Chan et al., 2022) or become a "hub organization" for entrepreneurial ecosystems (Schaeffer and Matt, 2016; Youtie and Shapira, 2008). Such institutional and organizational developments can foster the inculcation of a more entrepreneurial culture (Bercovitz and Feldman, 2007; Feldman and Stewart, 2008; O'Gorman and Roche, 2014; Kalar and Antoncic, 2015; Schaeffer and Matt, 2016; Youtie and Shapira, 2008). For academic engagement, however, the value of such spaces is linked to their ability to promote trust, learning, and understanding, whereby peers become better able to influence (and learn from) one another (Perkmann et al., 2013, 2021; Bozeman and Gaughan, 2007).

Such spaces can be presumed to be particularly relevant for research of an interdisciplinary nature. While researchers from the same discipline or ones that have worked together in the past might not require convincing of why they should commit to IKA for their career prospects, this is less so for scientists which have little experience with interdisciplinary research or even view it as adverse to professional advancement, due to missing legitimacy (Bromham et al., 2016; Baum and Bartkowski, 2020; Bikard et al., 2019). In examining obstacles for inventive research teams, Bercovitz and Feldman (2011) noted the high coordination costs necessary, to bring together researchers across departments: *"the challenge of achieving such coordination increases, and the likelihood of innovative success decreases, the greater the number of departmental and organizational boundaries spanned by the team"* (ibid.: 91). Here, informal aspects such as prior social ties among partners, having worked together in the past, and knowing how to communicate with one another, are key for overcoming and bridging the cognitive distance between different knowledge areas (Nooteboom et al., 2007, vom Stein et al., 2015). Bridging this cognitive distance proves to be key to knowledge creation in interdisciplinary settings, along with facilitating the highly impactful and visible research that is relevant for grand societal challenges (Nonaka and Toyama, 2003; D'Este et al., 2019). Haeussler (2011) also found that researchers are more encouraged to share valuable information if operating under expectations of reciprocity and norms toward 'open science'. The potential for research collaborations, of an interdisciplinary nature, thus depends on knowing what the other party has to offer and its willingness to share such (valuable) resources.

Thus, the challenge remains how actors in a new IKA, with universities being the focus of attention, can facilitate its emergence and build legitimacy to establish the new knowledge area. Drawing on the concepts of innovation ecosystem, emergence, and academic engagement, this study aims to shed light on what drives IKA emergence and specifically how diverse actors within universities, and between universities and industry, can co-develop legitimacy across disciplinary and triple-helix boundaries.

3. Research design

3.1. Case selection

Against this background, one vivid example of a knowledge area emerging from interdisciplinary research can be witnessed in the growing domain of "synthetic life sciences". This domain is situated at the intersection of a range of knowledge fields like biotechnology, material science, electric and computer engineering, and systems or evolutionary biology. Propelled by hallmark breakthroughs such as the creation of the first synthetic genome (Gibson et al., 2010) or the use of metabolic engineering to produce the antimalarial drug *artemisinin* (Martin et al., 2003; Kung et al., 2018), there is growing recognition of the substantial promise supported by the emerging interdisciplinary knowledge area. This could entail "designer" bacteria that perform tasks such as clean production of biofuels, bioremediation, individualized medical treatments (Specter, 2009), and boosts to agricultural yields, by enhancing essential processes like photosynthesis or nitrogen and carbon fixation (Choi et al., 2016; Wurtzel et al., 2019; Miller et al., 2020). Firms and commercial interests are also taking note, e.g., reflected by attempts to create enzymes that digest, and thus facilitate recycling of, plastic (Palm et al., 2019).

Synthetic life sciences sit at the convergence of life sciences, computer sciences, engineering, and other previously separate research streams, underscoring its essentially interdisciplinary character (Calvert, 2010; Way et al., 2014; Shapira et al., 2017; Baaden et al., 2024). The profound challenges that are inherent from the interdisciplinary nature of the research present difficulties for horizontal technology transfer, i.e. from science area (a) to area (b), like the application of data science to microbiology (Mansfield, 1982).

Beyond those fields most often associated with technology development, the potential for ethical, legal, and social implications (ELSI) signals the need for more researchers from the social sciences to take active interest in the synthetic life sciences to build legitimacy (Kuzma, 2015; Trump et al., 2020; Shapira et al., 2017). According to Trump et al. (2020), the ability to motivate broader, deeper collaborations within the synthetic life sciences marks a key feature of the transition from "the first twenty years of synthetic biology development" and its strong focus on "technological innovation and production innovation". Namely, they argue: "the next twenty should emphasize the synergy between developers, policymakers, and publics to generate the most beneficial, well governed, and transparent technologies and products possible." Although the field of synthetic life sciences might be considered rather "mature" in certain respects, its continued emergence as a knowledge area is thus contingent on integrating increasingly diverse types of knowledge and expertise. The nature of such challenges also underscores how the synthetic life sciences are relevant, and potentially exemplary, for understanding emergence of IKA, especially when it comes to building legitimacy.

We argue that it is necessary to consider how universities are specifically contributing to the further emergence of synthetic life sciences, namely, by bringing more forms of expertise into the fold and establishing incentives and support for such collaborations. Given the challenges which confront the synthetic life sciences – technical, regulatory, social, and acceptance-related – the centering of universities as site and space for interdisciplinary collaborations and the integration of knowledge is beneficial for a variety of reasons, not least how it highlights the interplay between university initiatives or structures and the decisions of individual researchers within this ecosystem.

Toward this end, we employ the unique case of a German university in the region of North-Rhine Westphalia that is in the process of rebranding itself in relation to the "synthetic life sciences". As a complement to discussion of the "entrepreneurial" mission of universities (Allen and O'Shea, 2014; Kalar and Antoncic, 2015; Wang and Lu, 2021), we note the desire to establish its reputation in relation to the synthetic life sciences – bringing about needed changes for education of students, how the university and its researchers engage with local community and industry, and the effective incentives for hiring and promotion of academic personnel. Thus far, this has yielded the sharing of facilities under this banner, the establishment of a new Chair, and a joint cross-faculty study program bridging the various disciplines. Nonetheless, despite developments at an organizational level, the question remains to what extent these have affected the perceptions and decision-making of individuals occupying different roles across the ecosystem and, as such, proven successful in motivating the alignment of their interests and goals in pursuit of broader collaborations.

3.2. Group concept mapping

Group concept mapping (GCM) is a structured methodology for organizing and integrating ideas and perceptions of a heterogeneous set of actors (Kane and Trochim, 2007; Kane and Rosas, 2018). One of its main advantages over other approaches is its capacity to center individual perspectives without necessarily losing sight of the broader ecosystem. The name states its core features: (1) its ability to enable collaborative, participatory engagement with communities of interest; and (2) use of a mixed-methods approach to develop visual maps that elucidate findings. Insights gained from GCM help to identify the issues understood to be of highest priority, how different clusters of ideas relate to one another, if there are signs of consensus within an emerging ecosystem, and a silhouette of a common vision toward which these actors collectively strive. In other words, even if not yet widely employed, this method can prove particularly useful for revealing the core perceptions and components that underlie IKA. Unlike interviews and most qualitative approaches, for instance, the visual outputs produced by GCM lend themselves to communication and exchange around the results, in a way not usually possible for qualitatively rich data. Increasingly, GCM is finding broader application regarding the factors that drive adoption of novel technologies, e.g., in terms of the emergence of novel value chains or technology transfer among stakeholders (Berg et al., 2018; Borge and Bröring, 2020; Borge et al., 2022; Pelletier and Cloutier, 2019). As a result, there is growing appreciation of the insights that GCM can deliver, i.e., from an actor-based perspective and with a specific focus on novel technologies and practices. GCM is comprised of five steps (see Table 1), which we now enumerate.

Steps 1 & 2: Preparation and idea generation

In keeping with the participant-driven ethos of GCM, the preparation phase is the only one where researchers assume an active role: to recruit participants from across the ecosystem and to set the focus prompt. The focus prompt represents an incomplete sentence which participants are asked to complete and, in so doing, provides answers to the focal question. Befitting our university setting, we selected 11 participants, using a snowball approach, so that distinct perspectives on drivers of synthetic life sciences were represented for this emerging

Table 1
Group concept mapping research steps.

Step 1: Preparation	Step 2: Idea generation	Step 3: Data structuring	Step 4: Analysis	Step 5: Results and evaluation
- Define context of study	- Group discussion around focus prompt (N_{GD} = 11)	- Online survey via Global MAX software (N = 49);	- Create point map using multidimensional scaling	- Generate visual outputs (cluster rating maps; pattern matches; go-zone)
- Recruit participants	- Finalize list of statements on drivers (k = 55)	- Sort drivers into piles based on conceptual similarity (N_S = 44);	- Generate possible cluster maps using hierarchical cluster analysis	- Highlight points of agreement and disagreement within the invention ecosystem
- Develop focus prompt: *"Perceived drivers for the emergence of synthetic life sciences are …"*		- Rate drivers according to importance (N_{R1} = 48) + changeability (N_{R2} = 45)	- Select 8-cluster solution and assign names using input from participants	- Identify key capabilities that are missing and roles which remain un(der)occupied

Note: Number of participants in online brainstorming (N_{GD}); Number of participants who completed (at least) one part of survey (N); Number of participants who completed sorting task (N_S); Number of participants who completed rating for importance (N_{R1}); Number of participants who completed rating for relevance (N_{R2}).

interdisciplinary invention ecosystem: 2 professors; 2 younger researchers at a MSc or PhD level (both previously participated in iGEM); 3 from administration; and 4 from industry, two each from large (multinational) firms and small or medium enterprises (SMEs). In this way, we ensured all participants had some degree of expertise and familiarity with synthetic life sciences while also bringing their own perspectives.

To examine the emerging IKA of synthetic life sciences, we used the focus prompt of "Perceived drivers for the emergence of synthetic life sciences are …". Group discussion lasted about 2 h, with it then transcribed before being screened independently by two researchers to generate an initial list of 79 statements. Given that many statements duplicated one another, deliberation and discussion returned a final list of 55 broadly unique statements (Table 3).

Step 3: Data structuring

After the initial group discussion, we expanded our sample in order to ensure a broad representation of the ecosystem. To this end, we used snowball sampling (where they were recommended by prior participants) and identified individuals by looking at the staff directory at the case university. As such, we included researchers from disciplines like medicine and philosophy alongside those from the synthetic life sciences, as well as additional participants from the groups represented during the first phase. In total, 49 participants completed at least one part of the GCM. However, as not every participant completed all parts, we ultimately had rating (importance) data for 48 people; rating (changeability) data for 45; and sorting data for 44.[1] The breakdown of the full sample (n = 49) by type of actor is given in Table 2.

Statements were programmed into the Global MAX software (Concept Systems Incorporated, 2019) so all further tasks can be undertaken online. This first entailed sorting and rating of provided statements by a larger sample of participants, followed by questions regarding age, gender, prior knowledge about synthetic life sciences, and the actor group to which they belonged. We omit discussion on gender and prior knowledge, as neither were found to have a broad influence on perceived ratings. In case some participants' expertise was not directly in synthetic life sciences (mostly relevant in the case of professors from other disciplines or potentially some administrators), we offered a brief overview that highlighted potential applications at the outset of the online GCM. To clarify, the inclusion of such actors' perspectives was nevertheless deemed relevant given that, while not presently engaged with the synthetic life sciences, they possessed important skills and expertise for the broader assessment, understanding, and development of the synthetic life sciences, including in a more interdisciplinary fashion (Kuzma, 2015; Trump et al., 2020; Shapira et al., 2017). In other words, such experts could provide a dedicated perspective relevant to the emerging IKA of synthetic biology, through

Table 2
Sample breakdown by type of actor.

Type of actor	
Researcher (in synthetic life sciences)	14
Researcher (from another discipline)	9
Student	8
Industry (large multinational firm)	4
Industry (small or medium enterprise)	4
University administration (e.g., at Dean level and related to technology transfer)	10

[1] Sorting data had to be excluded for three people, who either grouped more than one statement into an assorted "Other" pile or failed to sort them in terms of conceptual similarity.

their expertise in one of its constituent domains or disciplines.

Participants were asked to undertake two tasks, rating and sorting of the statements. *Rating* centered on two dimensions – changeability and importance – on a 5-point scale (with 1 = "unimportant" and 5 = "very important"). Regarding changeability, participants were asked to evaluate how easy it would be "to imagine current conditions changing or if the potential for change was likely to exceed reasonable efforts, costs, etc.". This dimension helps to gain insight into perceptions of the extent to which the current situation and environment would facilitate or allow for the emergence of the drivers under consideration. Whereas other GCM studies have for instance examined ratings of importance along with relevance or feasibility, we introduce and use the notion of changeability to better encapsulate the sense of an ecosystem (potentially) in flux. Furthermore, by comparing the data for the two, we can identify statements perceived to be both significant and feasible.

Sorting of statements involved participants assigning each statement to a group, before assigning a label of their choice. Participants were instructed to sort statements "intuitively" to reflect their degree of conceptual similarity. It was emphasized there are no right or wrong answers and that, if desired, statements could be sorted into piles of one but not into "miscellaneous" piles or to reflect a form of evaluation, e.g., positive vs. negative, or important vs. unimportant.

Steps 4 & 5: Analysis, results and evaluation

Once we had sorting and rating data for all participants, we generated visual maps which elucidate the (collective) representations of synthetic life sciences in the innovation ecosystem in three ways. The first entails identification of clusters and how these relate to one another. We used the Global MAX software to develop a *cluster map* via two-dimensional non-metric multidimensional scaling and hierarchical cluster analysis (see Appendix). Names assigned to the clusters are based on actual descriptions that participants assigned to the piles of statements. In specific, the more a name was linked to a given set of statements, the greater the priority assigned to it by the software in the total list of names (see Appendix).[2] For each cluster and statement, bridging values were calculated as well, ranging from 0 to 1. They reveal how often a statement is grouped with others into a pile. The lower the bridging value of a statement, the more stable its position on the map and the more closely related it is to other statements in its cluster.

As a second form of visual presentation, we included the rating information from participants (here focusing on importance) to generate a *cluster rating map*. Those clusters rated (on average) as more important by participants are portrayed with more layers. By looking at differences in the number of layers across this map, we can gain insight into relative disparities in (average) importance.

The third form of visual presentation focuses on actor-level perspectives. Using the rating data for importance and changeability, we develop *pattern matches* that provide a side-by side comparison of how perceptions vary for the various actors in the innovation ecosystem. Appearing as a "ladder" graph where uneven or 'crooked' rungs reflect variation in cluster ratings, these figures illustrate areas of (dis)agreement across actors as well as how a given cluster is rated differently across the entire ecosystem.

To offer more concrete recommendations for those working in ecosystems similar to the one in the case, we also develop and discuss a so-called go-zone chart by plotting rating data for the two dimensions of importance and changeability against one another. The go-zone chart outlines the kinds of concrete initiatives deemed by the various groups of actors to be both important and changeable, thus providing a list of ideas and proposals for those wishing to nourish the emergence of this innovation ecosystem.

4. Findings

4.1. Drivers for the emergence of synthetic life sciences

Eight clusters were identified using the Global MAX software (specifically, two-dimensional non-metric multidimensional scaling and hierarchical cluster analysis). The clusters represent the key drivers for the emergence of synthetic life sciences. By way of a summary of constituent statements for each of the clusters (Table 3 to 10), we offer a short description before proceeding with how the clusters relate to one another.

1. *Reservations of the general public*: reasons for scepticism and concern from the public and society, including the ethical and political implications of synthetic life sciences.
2. *Proactive positive communication*: potential strategies and solutions to improve overall perceptions of synthetic life sciences and related applications.
3. *Regulatory realities*: national and international shortcomings in the regulatory system which prejudice public perceptions and serve as an obstacle to broader research support.
4. *Everyday relevance*: shortcomings related to the vertical transfer of knowledge from research in order to ultimately deliver applications with real-world benefits for clients and consumers.
5. *Research funding and framework conditions*: research-specific issues and difficulties that inhibit access to funding or the ability to do interdisciplinary research more generally.
6. *Start-ups and transfer*: potential value propositions and crucial incentives that facilitate vertical transfer of knowledge and technology and, thus, the emergence of academic spin-offs or university-industry collaborations.
7. *Interdisciplinary research*: the relevant actors, motivations, and capabilities which engender both interdisciplinary collaboration and further development of novel technological discoveries.
8. *Opportunities for science*: the more technology-related developments and their ability to engage the interest and motivation of researchers in the synthetic life sciences as well as wider attention across the ecosystem.

Table 3a
Cluster–1 - Reservations of the general public.

Statements	Bridging value
	0.18
33. Strong reservations against genetic engineering (i.e. topic quickly devolves into a shouting match)	0.00
1. Bias within the media against gene technology, including in children's programming	0.02
49. People outside of science are uncertain or fearful of new concepts	0.02
7. Potential (negative) associations between "synthetic" and artificiality, e.g. artificial intelligence	0.07
15. "Scorched" concept of biotechnology in the public (especially for food-related applications)	0.11
32. Limited interest or engagement from certain segments of society	0.11
19. Limited attention span with regard to complicated topics	0.16
4. Limited trust in industrial actors	0.19
51. Playing down of the positive aspects whenever opponents of gene technologies take part in government negotiations	0.27
41. Ethical questionability of changes to the genetic code, e.g. in order to correct genetic "mistakes"	0.33
40. Political parties do not want to alienate voters	0.45
17. Ethical discussions concerning the creation of life	0.48

[2] As all steps were conducted in German, we needed to translate the cluster names. Substantial care was taken to ensure this resulted in no change in meaning. Details on original statements and cluster names are available on request.

Table 3b
Cluster–2 - Proactive positive communication.

Statements	Bridging value
	0.74
26. Positive views of medical applications (e.g. artificial organs) and new therapy possibilities	0.66
23. Individuals, and specialists in particular, who can communicate scientific topics in a fair and non-polarizing fashion	0.66
54. Lever or handle by which public interest can be generated, e.g. in relation to global food security or plastic waste	0.71
30. Integration of new ways of thinking into research projects, e.g. emphasize outreach and informing the public from the outset	0.71
13. Positive coverage of the success (of students) in “iGEM” ("international Genetically Engineered Machine") competitions	0.81
18. Early-education initiatives (in primary schools) about scientific research	0.90

Table 3c
Cluster–3 - Regulatory realities.

Statements	Bridging value
	0.66
37. Concern that universities get caught in the crossfire of non-governmental organizations (NGOs) such as Greenpeace	0.56
35. Variations in risk tolerance across countries, e.g. between the US and EU	0.59
52. Disagreement about the need for new concepts or terminology	0.70
5. New technological possibilities that again bring about regulatory uncertainty	0.78

Table 3d
Cluster–4 - Everyday relevance.

Statements	Bridging value
	0.59
9. Lack of basic scientific knowledge in the lay public (e.g. about DNA)	0.50
20. Lack of products with everyday relevance, e.g. PVC ("polyvinyl chloride") or fluoride chemistry	0.53
31. Difficulties (in industry) of communicating new concepts to clients and consumers	0.56
55. Performance of new products and technologies not yet validated in difficult real-world contexts (e.g. microorganisms able to break down plastic in Arctic environments)	0.67
21. Only “breakthrough papers” (e.g. about minimal cells or microplasma) but without any genuine breakthroughs for everyday life	0.67

Table 3e
Cluster–5 - Research funding and framework conditions.

Statements	Bridging value
	0.46
24. Necessary licenses not always granted, e.g. for foundational research and use by start-ups	0.37
47. Unequal regulatory burdens across firms, so that technologies are not uniformly viable	0.40
39. Limited funding for biotechnology in North Rhine Westphalia	0.42
10. Unequal global playing field, e.g. first-mover advantages of researchers and companies in USA	0.42
38. Difficult local conditions in Germany and the EU	0.46
12. Lack of qualified experts to serve as reviewers for interdisciplinary grant applications	0.48
25. Limited funding opportunities for truly interdisciplinary collaboration (e.g. from the German Research Foundation (DFG))	0.53
46. Investor demand for hockey-shaped (i.e. fast-growing) revenue curves	0.54
43. Growing dependence on industrial actors, e.g. for the funding of research projects	0.55

Table 3f
Cluster–6 - Start-ups and transfer.

Statements	Bridging value
	0.96
36. Prospect of more cost-effective production (i.e. more important than any reductions in environmental pollution)	0.88
29. Investor willingness to fund research and development, as well as initial commercialization	0.99
2. Incentives for spin-off companies included as part of funding programs	1.00

Table 3g
Cluster 7 – Interdisciplinary research.

Statements	Bridging value
	0.58
16. An interdisciplinary focus, where all disciplines feel themselves to be well-represented	0.29
11. Common terms (or long-term vision) able to motivate the participation of other faculties such as medicine and philosophy	0.52
53. Researchers with experience engaging in interdisciplinary collaboration	0.62
48. Willingness of professors outside of natural sciences (e.g. in bioinformatics) to apply their expertise	0.89

Table 3h
Cluster–8 - Opportunities for science.

Statements	Bridging value
	0.16
42. Potential for quicker development (in space of a few weeks) of necessary drugs and pharmaceuticals, e.g. in the case of cancer	0.02
22. Technical capability to synthesize longer sequences of DNA	0.03
50. Automatization of prototype development, i.e. runs over night and ready the next morning	0.05
45. Acceleration toward the commercialization of flavor production, e.g. down to three or four years	0.08
27. Revolutionary developments (e.g. CRISPR/Cas) that could not be previously predicted	0.10
8. Breakthrough technologies that are able to satisfy all safety requirements	0.11
3. Radically new ideas which motivate scientists from different disciplines to work together	0.11
28. Development of new software that quickly analyzes and identifies (or produces) those proteins which are most relevant for customers	0.14
44. Developments in the direction of individualized medical treatments	0.24
6. Increasing usage of “open source” approaches, whereby relevant information and data is accessible and immediately available to everyone	0.30
14. Modern, young, open sector with many opportunities for start-ups, including academic spin-offs	0.30
34. (Industrial) applications with potential environmental benefits	0.46

Fig. 1 displays the cluster map with eight clusters derived from 55 statements, each point representing one of the statements. It is the relative position of clusters, not their location on the map, which is relevant for interpretation.

Low bridging values for “opportunities for science” (*0.16*) and “reservations of the general public” (*0.21*) indicate most participants grouped the respective drivers in a similar fashion, and that these drivers jointly expressed the meaning of the cluster. This speaks to how much the emergence of synthetic life sciences centers on the (adverse) perceptions of the public and sizable opportunities for new technological developments and achievements. Rather than, for instance, the creation

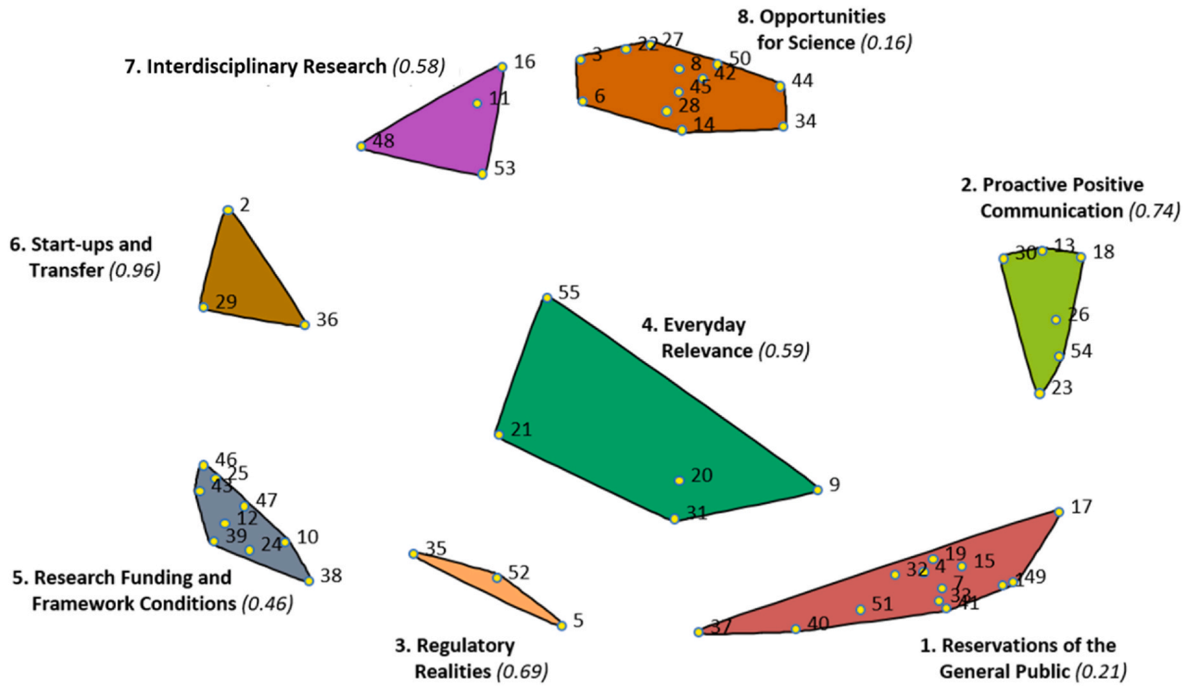

Fig. 1. Cluster map based on drivers for the emergence of synthetic life sciences.
Note: Numbers in parentheses reflect the bridging values of the clusters.

of value, it is thus these drivers that take center stage. In contrast, the high values of "start-ups and transfer" (*0.96*), "regulatory realities" (*0.69*), and "proactive positive communication" (*0.74*) present these as bridging categories which link to and describe the clusters around them. The best example here is "start-ups and transfer", with this cluster offering a way to connect "opportunities for science" and "interdisciplinary research" with "research funding and framework conditions". The inability to attain funding or deliver on the promise of new technology can thus be explained by, e.g., the willingness of investors to grant funding for research and development (#29) and the lack of commercial advantages such as superior cost efficiency (#36). Such insights take on added importance given the emphasis by Shapira et al. (2017: 1457) on the role of "research sponsorship" in the emergence of the synthetic life sciences, most of all to "acquire recognition … and build a critical mass of interdisciplinary and institutional collaborators". Despite the promise of synthetic life sciences, actors specifically stressed the commercial realities as significant hurdles for research projects and interdisciplinary collaborations ultimately bearing fruit in the real world (Delebecque and Philp, 2015). Engaging partners in industry to better understand their needs and concerns could thereby offer a pathway for increasing R&D funding and having the necessary resources (Shapira et al., 2017) but ensuring transfer from research institutes to commercial actors (Borge and Bröring, 2017, 2020; Bercovitz and Feldman, 2011).

4.2. Importance of drivers for the emergence of synthetic life sciences

We turn to the *cluster rating map* for importance. Extending the map in Fig. 1 by now integrating rating data for each cluster, we can hereby gain insight on the relative disparities in their (average) importance. The clusters with the most layers – "opportunities for science" and "proactive positive communication" – were rated as most important for the IKA as a whole. Intriguingly, it is strategies to more deeply engage with the public that appear to drive emergence of this IKA, such as individuals able to communicate scientific topics in a fair, non-polarizing fashion (#23) or linking synthetic life sciences to eye-catching issues like plastic waste and global food security (#54). As a mix of ways for reaching out to the public and presenting the technology, this cluster emerges as a list to 'de-escalate' the public discourse, overcome the 'anchoring' of synthetic life sciences, and potentially deliver on its technological promise. Moreover, the focus throughout the IKA on "proactive positive communication" signals a more forward-looking approach given the limited importance of the clusters "reservations of the general public" and "regulatory realities". While each was the object of much consternation in initial discussions, once participants (from the larger sample) were asked to weigh their relative importance, they turned out not to matter much.

We find that participants in this IKA assigned greater significance to two types of drivers at the stage of emergence: those around technical developments in the research field and those promoting deeper public engagement. Here we note that Thomas and Autio (2014a, 2015), in their analysis of digital service platforms, find that the main drivers during the 'initiation' phase related to resources and technology; so-called institutional and context drivers only became important later. Away from the digital context, the potentially contentious character of synthetic life sciences renders more *contextual* drivers such as "proactive positive communication" key from the outset. However, as depicted by the importance of "interdisciplinary research" and "start-ups and transfer", such *resource*-related drivers, which affect the potential for interdisciplinary collaboration and incentives and support from external partners (e.g. investors), also emerge as integral.

4.3. Actor-level perspectives on drivers for the emergence of synthetic life sciences

Pattern matches, developed using the rating data for importance and changeability, help to explore how perceptions of the IKA vary by actor type. As the importance ratings of researchers did not significantly vary by discipline, we examined these jointly as "researchers" (Fig. 3).[3] Similarly, given the lack of differences in ratings for the industry sub-

[3] As changeability ratings did vary, it was necessary to consider these separately. In the end though, we opted to exclude researchers from other disciplines (and students) to simplify the pattern match for changeability (Fig. 4).

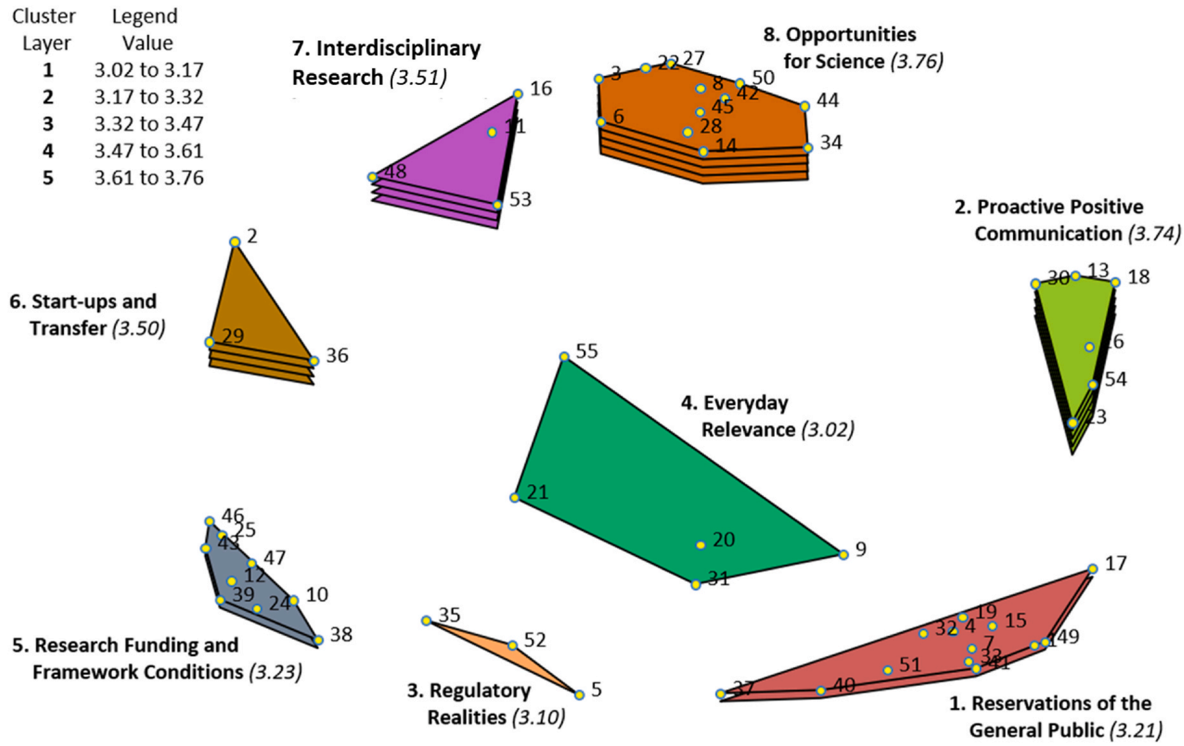

Fig. 2. Cluster map based on importance of drivers for the emergence of synthetic life sciences.
Note: Map shows 55 statements grouped into eight clusters (average ratings in parentheses). Ratings on a 5-point scale, with ratings from 1 to 3 indicating a statement (or cluster) is deemed relatively unimportant.

groups, we take them together as "industry" for subsequent analysis. Appearing as a "ladder" graph where uneven or 'crooked' rungs reflect variation in cluster ratings, we reveal that researchers tended to perceive all clusters as less important. However, while such results point to broad pessimism of researchers, the prospect that differences in rating scales could mask (dis)agreement in the relative priority of clusters leads us to decide to instead focus on the overall rankings in the rest of the section.[4]

The main takeaway here is that the priority and ranking of clusters in terms of importance turns out to be broadly stable across actors. As a first finding, this points to the potential for *alignment* within this emerging ecosystem, even if at present this mostly pertains to the drivers that matter rather than their overarching interests and goals. In any case, this speaks to the ongoing *co-evolution* of the ecosystem around a core set of drivers as well as a growing sense of *legitimacy* in the more cognitive sense of the term (see Thomas and Autio, 2014b). Note that the clusters of "opportunities for science" and "proactive positive communication" always rank in the top three – recall these also featured the highest average rating for importance (Fig. 2). In fact, the only group not ranking them as the top two is administration.

Yet, the weight of administration on "interdisciplinary research", ranked fifth by researchers, offers an alternate viewpoint. Notably, this cluster highlights the importance of a more "interdisciplinary focus" (#16) and "long-term vision able to motivate the participation of other faculties" (#11). With this, we see a shift from acknowledging the interdisciplinary nature of the synthetic life sciences to identifying and developing the types of changes needed to bring such collaborations to bear. Such a perspective is also reflective of a culture of "open science", wherein information is more freely shared across faculties and with partners in industry (Haeussler, 2011). Insofar as this deepens and enriches the kinds of knowledge and expertise present and promotes stronger linkages to those in industry (and their perspective), this mirrors the impetus toward "entrepreneurial universities" and a deep culture of innovation and entrepreneurship among researchers, staff, and students (Allen and O'Shea, 2014; Kalar and Antoncic, 2015; Wang and Lu, 2021). At the same time, such changes are easier said than done owing to the need to train students from different faculties and prepare early-stage researchers to have the necessary skills in data science, statistics, modeling, and classical natural science so that they can be effective collaboration partners (Delebecque and Philp, 2015). Moreover, researchers, especially those not from the natural sciences (see #48), are unlikely to collaborate on a project of this kind, let alone take time to become familiar with the approaches and mindsets of counterparts, if doing so were to hamper their professional prospects (Müller and Kaltenbrunner, 2019; Cornell et al., 2013; Bromham et al., 2016; Baum and Bartkowski, 2020).

In addition, it is the same two or three clusters are always rated as the least important: "everyday relevance", "regulatory realities", and "reservations of the general public". The fact that some cluster ratings are close to or beneath the mid-point of 3 also denotes that they are not only relatively less important but rather unimportant. Especially concerning "reservations of the general public" and "regulatory realities", this stands in stark contrast to how, e.g., "strong reservations against genetic engineering" (#33) or "bias within the media" (#1) in the case of the former, and "variations in risk tolerance across countries" (#35) and "regulatory uncertainty" (#5) in the latter, typically dominate media attention and public scrutiny (Torgersen, 2009; Frewer et al., 2011). At the same time, it turns out that academics place greater importance on reservations of the public, while industry identified it as the second-least important cluster. We thus surmise that it is researchers, not industry, which perceive themselves to be most exposed to the criticism and complaints of the general public.

Turning to the pattern match according to changeability (Fig. 4), the

[4] For instance, though students and researchers both ranked "opportunities for science" as the most important cluster, this is overlooked if we focus on how ratings significantly differ, 3.55 for researchers versus 4.09 for students ($p < 0.01$).

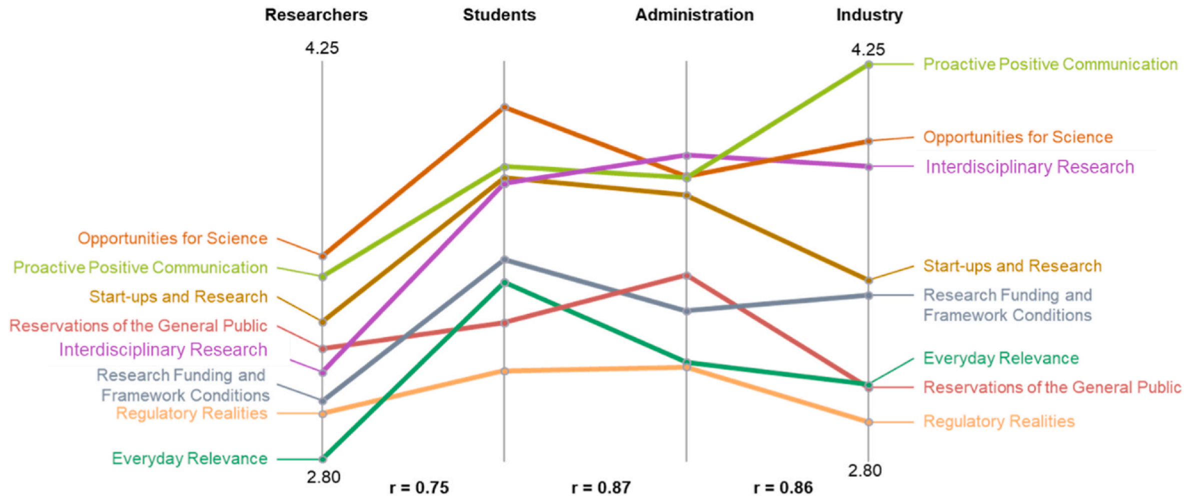

Fig. 3. Pattern match based on importance ratings for the emergence of synthetic life sciences.
Remark: Relationships between actors' ratings of the relative importance of ideas averaged across clusters presented.

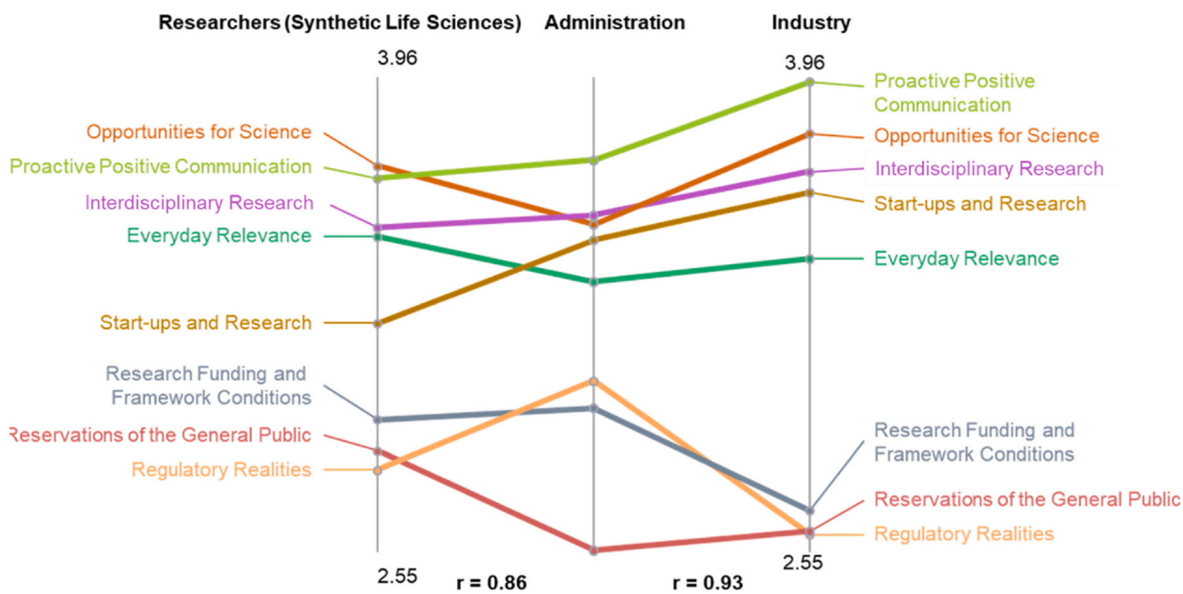

Fig. 4. Pattern match based on changeability ratings for the emergence of synthetic life sciences.
Remark: Relationships between the actors' ratings of the relative changeability of ideas averaged across clusters presented.

notable upshot is the level of coherence among researchers from synthetic life sciences, administration, and those in industry. Indeed, though we omitted students and researchers from other disciplines for this analysis, we find that a broad consensus exists among the other three groups regarding drivers that can be expected to change. Correlations between the ratings here are all quite high, and furthermore the priority assigned to the clusters, as well as their overall ratings, do not differ dramatically. What is more, the clusters break down into three groups: firstly, there is a highly changeable cluster of "proactive positive communication", "opportunities for science", and "interdisciplinary research" – with the three consistently ranked as the most changeable clusters, and all with average ratings above 3.5.[5] Secondly, we have the intermediate cluster of "everyday relevance" and "start-ups and transfer", which, although rated well above the mid-point of 3.0, are still generally below the higher cluster. Lastly, we have an unchangeable cluster which is comprised of "research funding and framework conditions", "reservations of the general public", and "regulatory realities". Although these clusters were rated as relatively less important, the degree of pessimism expressed by all actor groups still stands out – in fact, only one of nine ratings were above 3.0, revealing that these clusters were seen as both relatively and absolutely less changeable. However, it is worth noting that clusters deemed least likely to change tended to be ones in which others held more sway, e.g. regulatory authorities, funding agencies, political parties, NGOs, the public. As such, low ratings could be interpreted as a signal that stakeholders believed they had little direct influence here in contrast to, for instance, "opportunities for science" and "interdisciplinary research". Nevertheless, given that funding from research sponsors is fundamental to having the resources, time and space to foster interdisciplinary collaborations in the synthetic life sciences (Shapira et al., 2017), it is possible that such perceptions are a glaring blind spot among those in this emerging ecosystem.

[5] The only group in the IKA to not rank these three the highest were students, who placed "everyday relevance" in the second spot, while bumping down "interdisciplinary research" to fifth with a rating of 3.00.

5. Synthesis and discussion

To synthesize and make these results more operable for practitioners and academics, we develop a set of propositions. Towards this end, one final visual output from GCM, the go zone chart (Fig. 5), is utilized to identify the initiatives deemed by the various actors in the IKA to be both important and changeable. Numbers next to the points identify the statement, and colors of the dots reflect the cluster. Along with the go zone, we offer an enumerated list of the statements (Table 4), so that it is possible for other interested parties to derive their own implications and determine the initiatives that best suit their purposes. As quadrants are segmented according to the means of the dimensions, the upper-right quadrant is comprised of statements above average in changeability and importance – that is, pointing to those initiatives able to deliver meaningful impact at relatively limited effort and cost. The following discussion therefore focuses primarily on this “go-zone”.

First, we highlight the clusters most prominent in the go-zone: “proactive positive communication” and “opportunities for science”. It is notable that the two account for 13 of the 19 statements in the go-zone, as well as occupy the top eight spots (by importance) – no other cluster provides more than two statements, with “regulatory realities” not represented at all. Moreover, we find that the results break down into three categories, which we use to derive propositions. Propositions thus consist of three types: (1) *capabilities* that are required or missing, including from the participation of specific actors; (2) specific *obstacles* having to be resolved for deeper interdisciplinary collaboration or public acceptance to materialize; and (3) prospective *selling points* of synthetic life sciences that can foster broader public or political acceptance. The following propositions signal the importance of universities (and their partners), as actors and how these can contribute to developing *capabilities*, resolving *obstacles*, and turning *selling points* into a guiding vision to foster the emergence of IKA.

Having examined the unique challenges and drivers of IKA, we stress the importance of centering the growing role of universities as key to the research and development of new technologies. This is particularly true of technologies emanating from IKAs, owing to the difficulty of attracting the full range of skills and expertise essential to success. Oftentimes, it is the contribution of universities to local economics and industry which tends to feature, that is, as sources of knowledge that can have broader value – even then, their importance for knowledge creation, developing a highly trained workforce, and facilitating job creation is continually underscored (Bramwell et al., 2012; Bercovitz and Feldman, 2006). As such, universities represent under-appreciated spaces for collaborative research and knowledge creation, most clearly if the activities of the university are framed around a specific mission.

Universities thus emerge as a type of ecosystem in their own right, not only in the geographic sense but also for the preeminence of knowledge creation and exchange, not least of an interdisciplinary nature. We therefore propose the notion of “invention ecosystem”, to emphasize such aspects and promote greater attention to related drivers and challenges – in doing so, we do not dismiss the role of universities toward innovation but rather ensure that focus on their contributions in this direction do not subsume those involving “invention”. Starting with the contributions of universities to local economics and industry, there is greater appreciation of their impacts where informal ties and forms of exchange prevail, of the kind which helps to promote trust, learning, and understanding across disciplinary boundaries (e.g. Bozeman and Gaughan, 2007; Perkmann et al., 2021). Here the finding from the extant literature that the social and “hard” sciences differ even in relatively fundamental aspects such as how knowledge is transferred is relevant, with those in social sciences more reliant on personal contacts and labor mobility (Perkmann et al., 2021; Bekkers and Bodas Freitas, 2008;

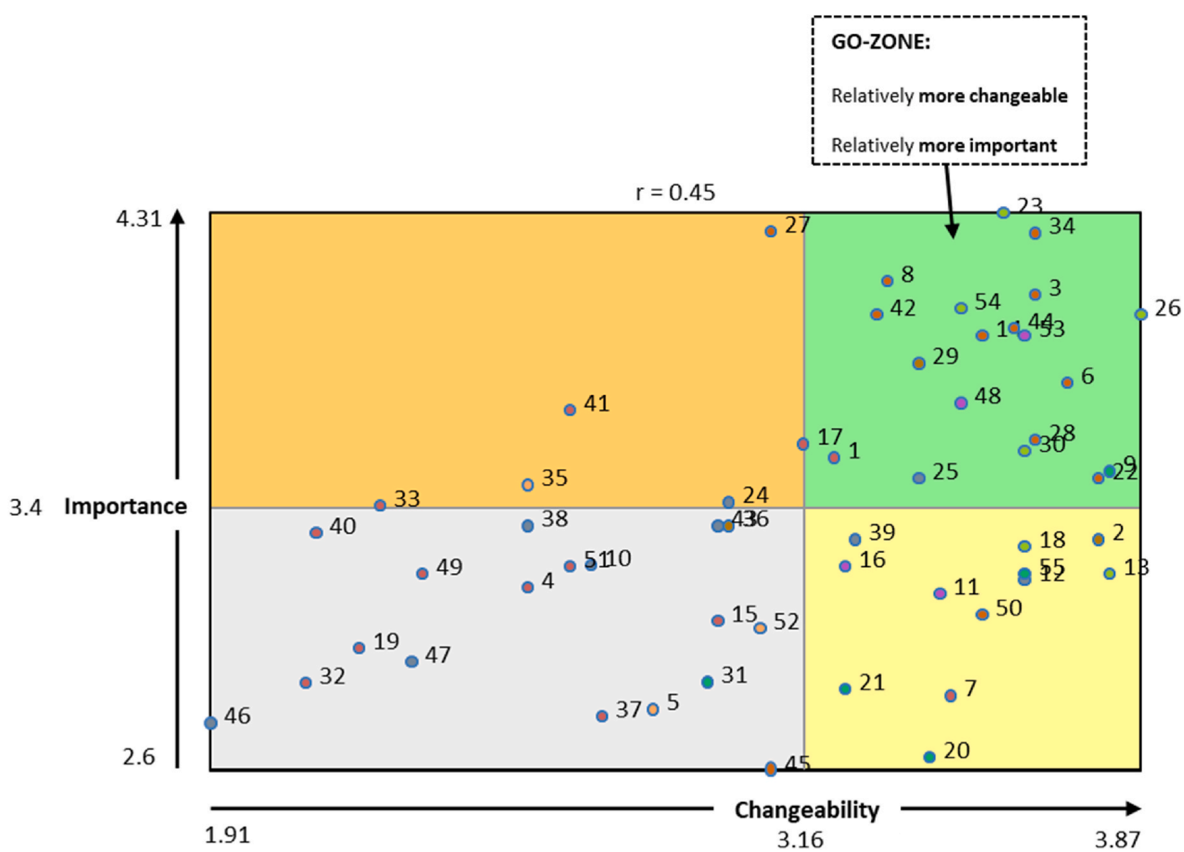

Fig. 5. Go-zone chart showing importance and changeability ratings for the 55 statements.
Remark: The four sectors are constructed using the average x- and y-values.

Table 4
"Go-zone" of all statements above average in importance and changeability.

Cluster no.	Statement no.	Statement	Importance rating	Changeability rating
2	23	Individuals, and specialists in particular, who can communicate scientific topics in a fair and non-polarizing fashion	4.31	3.58
8	34	(Industrial) applications with potential environmental benefits	4.25	3.64
8	8	Breakthrough technologies that are able to satisfy all safety requirements	4.10	3.33
8	3	Radically new ideas which motivate scientists from different disciplines to work together	4.06	3.64
2	54	Lever or handle by which public interest can be generated, e.g. in relation to global food security or plastic waste	4.02	3.49
2	26	Positive views of medical applications (e.g. artificial organs) and new therapy possibilities	4.00	3.87
8	42	Potential for quicker development (in space of a few weeks) of necessary drugs and pharmaceuticals, e.g. in the case of cancer	4.00	3.31
8	44	Developments in the direction of individualized medical treatments	3.96	3.60
7	53	Researchers with experience engaging in interdisciplinary collaboration	3.94	3.62
8	14	Modern, young, open sector with many opportunities for start-ups, including academic spin-offs	3.94	3.53
6	29	Investor willingness to fund research and development, as well as initial commercialization	3.85	3.40
8	6	Increasing usage of "open source" approaches, whereby relevant information and data is accessible and immediately available to everyone	3.79	3.71
7	48	Willingness of professors outside of natural sciences (e.g. in bioinformatics) to apply their expertise	3.73	3.49
8	28	Development of new software that quickly analyzes and identifies (or produces) those proteins which are most relevant for customers	3.62	3.64
2	30	Integration of new ways of thinking into research projects, e.g. emphasize outreach and informing the public from the outset	3.58	3.62
1	1	Bias within the media against gene technology, including in children's programming	3.56	3.22
4	9	Lack of basic scientific knowledge (e.g. about DNA)	3.52	3.80
8	22	Technical capability to synthesize longer sequences of DNA	3.50	3.78
5	25	Limited funding opportunities for truly interdisciplinary collaboration (e.g. from the German Research Foundation (DFG))	3.50	3.40

Martinelli et al., 2008). By more fully fulfilling the features of an invention ecosystem, universities would help bridge such disciplinary differences, or make them less restricting, perhaps mirroring the ability of novel organizational structures to bring to bear expertise from multiple knowledge fields (Perkmann et al., 2013; Bozeman and Gaughan, 2007). While this characterization has to date been employed in relation to research centers and other more quintessentially novel structures, the insights from our case indicate this could also be applicable for universities – novel more in how they are conceived rather than as an institution.

Proposition 1. *To foster greater legitimacy for emerging IKA, universities are essential as invention ecosystems that strengthen interdisciplinary collaborations and promote open and transparent sharing of knowledge.*

Signaling the kinds of *capabilities* that are required, the statement rated highest in importance was "individuals, and specialists in particular, who can communicate scientific topics in a fair and non-polarizing fashion" (#23). As a policymaker, one may wish to invest in attracting or developing individuals with such expertise, while administrative officials could seek to promote researchers with notable aptitude in this kind of task. Furthermore, given the emphasis within the go-zone on "researchers with experience engaging in interdisciplinary collaboration" (#53) or "willingness of professors outside of natural sciences (e.g. in bioinformatics) to apply their expertise" (#48), there is greater realization that changes at an organizational and institutional level are required. Here we underline the importance of some "guiding vision" to align the expectations and interests of actors (Smith et al., 2005) – to foster mutual awareness that participants are engaged in some "common enterprise" (Thomas and Autio, 2014b: 22). Similarly, to bring down boundaries across disciplines or between universities and industry, a couple university-focused, case-based studies demonstrated the important role of "boundary spanners", e.g. for promoting communication and the exchange of tacit and codified knowledge (Schaeffer and Matt, 2016; Youtie and Shapira, 2008). In fact, the case university in the current study is reflective of the notion of "knowledge hub" by Youtie and Shapira (2008), at least in aspiration. What the synthetic life sciences, as an example of IKA, further stresses is the need for greater consideration of ethical, legal, and social implications (Kuzma, 2015; Trump et al., 2020), not to mention potential concerns of public rejection (IRGC, 2010; Akin et al., 2017); unlike some other studies, this prioritizes a somewhat distinct set of skills and expertise, including with regards to scientific communication.

Proposition 2. *To foster legitimacy for emerging IKA, specialists with joint expertise in scientific communication and technical competencies are crucial for engaging with the public and clarifying the motivating vision that attracts more interdisciplinary collaborations within the ecosystem itself.*

Central to the perceptions and discussions of the actors in the IKA, we also identify the outline for a broader and more substantive role for administration. In part, this emerged from the implicit need for additional actors to facilitate the emergence of IKA beyond those that attract the lion's share of attention (i.e., in the academic engagement literature): academic scientists; technology transfer offices; firms or entrepreneurs (e.g., Feldman and Stewart, 2008; Perkmann et al., 2013, 2021). The greater role for administration could entail establishing the organizational incentives, norms, and rewards needed to attain alignment and consensus among the interests and goals of the (potential) partners (Kalar and Antoncic, 2015; Schaeffer and Matt, 2016; Youtie and Shapira, 2008). Here we note that organizational factors in the literature tend to be conceived in an incidental or difficult-to-define fashion, such as the quality of the educational institution or the degree of control exerted (Perkmann et al., 2013, 2021; Halilem et al., 2017). It is for this reason that Perkmann et al. (2021) indicate that understanding of the role of organizational contexts and incentives remains deficient at present. In this regard, the need to pay closer attention to the administration as an actor type comes to the fore. For example, given the need to foster the buy-in of 'external' actors such as funding agencies and the public (Shapira et al., 2017) or span boundaries and promote the exchange of both tacit and codified knowledge (Schaeffer and Matt, 2016; Youtie and Shapira, 2008), one can foresee the administration being well-suited to taking on more responsibilities. It could be notably well-situated to undertake activities for promoting the legitimacy of the emerging IKA (Hambrick and Chen, 2008) and helping to establish a hub with local economic and political actors (Schaeffer and Matt, 2016; Youtie and Shapira, 2008). Such a role would also dovetail nicely with the growing participation of administration on governing and advisory boards and steering regional economic development policy (Goldstein and Glaser, 2012).

Proposition 3. *To foster legitimacy for emerging IKA, a defined and stronger role for university administration is important to provide the resources, time, and space for interdisciplinary research collaborations to emerge and, potentially, to engage with and attract research funders and sponsors.*

In terms of key *obstacles*, there is ostensibly limited engagement with realizing the "opportunities of science" or undertaking the requisite activities for this to be possible. In particular, the limited consideration to linking the "synthetic life sciences" with emerging "grand challenges", beyond a nod to "sustainable plant production", emerges as problematic. Looking at Table 4, we highlight both the importance (and changeability) assigned to "radically new ideas which motivate scientists from different disciplines to work together" (#3). In other words, according to those within this nascent ecosystem, it is directly the appreciation of the knowledge and ideas embodied in the synthetic life sciences which is sufficient to encourage individual researchers, especially those in social sciences, to be able to envision how collaborations could advance their careers.

However, the (implicit) belief that the far-reaching potential of synthetic life sciences, to address key challenges and benefit society, is to an extent sufficient to overcome disciplinary boundaries and inclinations toward "silo thinking" is quite likely over-optimistic. Based on empirical research of IKA, the challenge of achieving a common terminology or shared set of aims is typically more difficult (Hambrick and Chen, 2008; Fagerberg et al., 2012; Landström and Harirchi, 2018). Implicit and underlying the willingness of academics (and others) to invest the time and effort needed to collaborate, the question of legitimacy confronts all novel IKA. With specific relevance for younger academics, much of the initial legitimacy building is tied to the actions of a dedicated community of academics, institutions, and committed external actors (Hambrick and Chen, 2008; Landström and Harirchi, 2018). Once in place, the novel field then becomes more attractive for others to work in – notably, those with expertise, knowledge, and skills not readily available at first. The extent to which "opportunities for science" can be realized emerges as less the outcome of natural, internally driven evolution than one much more externally oriented, driven by encouraging more participants to join – and thus centers crucially on legitimacy.

Proposition 4. *To foster legitimacy for emerging IKA, interdisciplinary research collaborations can be motivated by emphasizing the opportunities of (and setting the right incentives for) working on dynamic, emerging science and the potential for start-ups and academic spin-offs*

Another key implication relates to the importance of establishing a role for 'external' actors at a sufficiently early stage. We refer here to Thomas and Autio's (2014b) discussions of the wider and deeper foundations of "socio-political and cognitive legitimacy" to underscore how the emergence of IKA is dependent on much more than just the activities and goals of its members. Indeed, given the "fear of the fear of the public" (IRGC, 2010: 38) and possibly controversial nature of synthetic life sciences, contextual drivers are likely to be more important early on, with "proactive positive communication" offering an example in the current study. Making efforts to develop roles for other actors, from industry or the public, would thus prove beneficial. There is evidence that integrating users in technology development as "co-creators" often leads to more creative, easily implemented, and valuable ideas (Kristensson et al., 2004; Poetz and Schreier, 2012).

One prospectively simpler way to build legitimacy and grow this community might be to bootstrap such efforts on extant social ties and prior experience working together – in other words, the success of "invention teams" (vom Stein et al., 2015; Bercovitz and Feldman, 2011). A broad lesson from Haeussler (2011) is that the success of groups, as well as the willingness to share information and collaborate, depends on context, specifically the extent to which norms of "open science" prevail and encourage individuals to work together. To facilitate horizontal transfer of knowledge between and across disciplines, one solution, centered on academic environments and universities, could be initiatives and improvements that cultivate these invention ecosystems. Not to be underestimated here, it is important that the necessary resources for exploring potential collaborations be available, whether in the form of time and space or also infrastructure and equipment (Shapira et al., 2017). Moreover, a key prerequisite would be to institute a coherent, mutually significant understanding of why such research matters, one persuasive to many different actors and prospectively derived from their inputs and reflecting their diverse goals and perspectives.

Proposition 5. *To foster legitimacy for emerging IKA, the engagement of actors which are external to IKA is needed early on and constructively to benefit from their expertise and perspectives as well as to build a positive case to attract research sponsors and explore possible value propositions.*

Several *selling points* of synthetic life sciences and its applications were also identified by the go-zone. These provide potential avenues toward attracting public relevance and acceptance or interest from potential collaboration partners or innovators. In specific, we stress those with "environmental benefits" (#34) or relevance to "global food security or plastic waste" (#54), along with the distinct relevance of "medical applications" (#26). Given difficulties in terms of ensuring public acceptance and societal legitimacy, we thus envision "new therapy possibilities" (#26) and "individualized medical treatments" (#44) serving as initial "proofs of concept" that help to lay the groundwork for public (or investor) confidence. In fact, this kind of health-first strategy is often mooted in relation to gene technologies, given that the public holds a more favorable view of such applications (Hess et al., 2016).

Proposition 6. *To foster legitimacy for emerging IKA, broadly relevant benefits for human health, food, and environment are key selling points to ensure public (or industry) interest and acceptance.*

These selling points stress how GCM offers an opportunity for the various actor groups to collectively flesh out the kind of guiding vision that can align their goals and interests. By affording a chance to deliberate on the emergence of synthetic life sciences, we can identify the framings most likely to cultivate consensus. This includes helping students looking for promising topics for future research and to advance professional aspirations of researchers from different disciplines, or to impart consideration of commercialization potential even at the research stage, and to promote norms of "open science" and information-sharing across faculties (Haeussler, 2011). As a result, time and effort devoted to interdisciplinary collaborations should be viewed positively vis-à-vis tenure and professional advancement (Baum and Bartkowski, 2020; Cornell et al., 2013; Müller and Kaltenbrunner, 2019; D'Este et al., 2019). While we find that researchers from other disciplines tend to be most pessimistic about the emergence of synthetic life sciences, they were more hopeful in relation to "start-ups and transfer". Thus, if the intent is to engage with such researchers, then highlighting developments for start-ups and commercialization would be useful, e.g., to encourage those from philosophy or mathematics afforded limited opportunities in their day-to-day activities to utilize their research to contribute to society in this manner. For those with an interest in doing so, stressing the potential for academic spin-offs, or simply providing the resources and support for such discussions to take place (Shapira et al., 2017), as a part of funding programmes or as criterion in hiring or promotion decisions, may prove highly motivating for interdisciplinary collaborations.

6. Implications and future research

6.1. Theoretical and practical implications

This exploratory study made use of the mixed-methods approach of group concept mapping (Kane and Trochim, 2007; Kane and Rosas, 2018) to identify and understand drivers of IKAs. Employing synthetic life sciences as a case, we pursued an actor-based perspective of the drivers identified as most important and/or changeable, in addition to how this varies by type of actor. This enabled us to elucidate initiatives that promote IKA emergence, by emphasizing the role(s) of critical actors or how to potentially engage with concerns of the public. Second, by examining similarities across the actors, we highlighted potential areas of consensus regarding the emergence of IKAs. In this manner, we outline a guiding vision that could align the interests and goals of these different actors. Third, by conceiving of universities as interdisciplinary invention ecosystems, we underscore the preeminence of the knowledge creation and exchange, notably of an interdisciplinary nature, which can occur in such geographically proximate spaces. By engaging universities through this lens, we emphasize the unique drivers and challenges that emerge and provide a discussion of the kinds of changes that promote their emergence, particularly in relation to legitimacy building and promoting collaboration among different actors.

These insights contribute to the emerging body of literature on ecosystem legitimacy by proposing explicit mechanisms through which legitimation processes are operationalized (Thomas and Ritala, 2022). A mutual, shared understanding of what the IKA is about and what it seeks to achieve, and how it seeks to do this can be fostered via developing universities as invention ecosystems in their own right. This can be explicitly pursued through a more defined and stronger role for university administration (Youtie and Shapira, 2008). Subsequently, promoting the legitimacy of the IKA can be achieved by: attracting or developing specialists with joint expertise in scientific communication and technical competencies; engaging actors external to the IKA early on and constructively to benefit from their expertise and perspectives; noting the opportunities of interdisciplinary research collaborations vis-à-vis working on dynamic, emerging science and the potential for start-ups and academic spin-offs; and highlighting the benefits for human health, food, and environment are key selling points to ensure public (or industry) interest and acceptance.

Our proposed notion of universities as (interdisciplinary) invention ecosystems, and not fragments of wider innovation ecosystems, offers guidance for policy makers and university leadership for managing challenges related to interdisciplinary research and knowledge integration. We provide novel insights on the roles and capabilities required to align the interests and goals of actors. Even at an emerging stage of research and development, we identify discussion about value propositions and commercial viability, as articulated by the "start-ups and transfer" and "everyday relevance" clusters (Adner, 2017; Kapoor, 2018). Due to the large overlap between its views and those in industry, we envisioned a clear (albeit nascent) role for administration as an invention ecosystem leader during this phase (Dedehayir et al., 2018), by forging links and partnerships with local (and multinational) firms or facilitating collaborations between researchers from distinct disciplines (Allen and O'Shea, 2014; Kalar and Antoncic, 2015; Schaeffer and Matt, 2016; Wang and Lu, 2021; Youtie and Shapira, 2008). For this to be possible, administration will have to see its role explicitly in such terms and take steps to ensure it is granted relevant *authority* and *legitimacy* by the diverse actors in the ecosystem (see Thomas and Autio, 2014b for a discussion in the context of innovation ecosystems). In other words, it must conceive its role in relation to the whole ecosystem, and specifically in terms of the promotion of credibility, coordination, and trust (Bercovitz and Feldman, 2011; Haeussler, 2011). Absent that, a clear sense of who occupies this leadership role is likely to remain elusive, with researchers often leveraging their contacts to industry – acting as their own broker or boundary spanner (Long et al., 2013) – or relying mostly on inter-organizational networks.

Finally, once we start to envision universities as a fundamental component of (interdisciplinary) invention ecosystems, this helps policy makers and university leadership to identify investments that are urgently required. In this regard, we can observe the clear importance of further investment in the physical infrastructure, e.g., in the form of biofoundries for synthetic life sciences. Highlighted as a key logistical and technical barrier for research and development, Wurtzel et al. (2019: 3) characterize these as "versatile facilities that can execute some or all steps in the design-test-build-learn cycle" for the genetic programming of novel organisms. Calling for a "global alliance of biofoundries", Hillson et al. (2019) stress how such facilities represent a crucial hub within broader networks that teach and train new researchers and transform new insights into real-world applications. Not only is the term "hub" interesting here given its echoes to the relevance of universities within more entrepreneurial ecosystems (Schaeffer and Matt, 2016; Youtie and Shapira, 2008) – it also suggests that, instead of specific actors or firms, the central *platforms* of emerging invention ecosystems are increasingly important as the kinds of places and environments wherein generation and exchange of knowledge and ideas is facilitated across groups of actors. This could be facilitated, e.g., by training individuals to be effective collaboration partners and to leverage one another's capabilities or, more simply, providing the necessary resources and opportunities.

6.2. Limitations and future research

With an eye toward future research, we also highlight potential limitations. Research efforts which build on the current results while working to address these shortcomings could provide key insights on the conditions and drivers for the deeper, more rapid emergence of much-needed IKA. First, on a methodological note, concerning the focus group discussion, the relatively structured nature of the discussion, with only one person at a time able to talk, could perhaps have limited the overall flow and generation of ideas. In this regard, future studies could combine group concept mapping and technology-enhanced approaches to focus groups, wherein participants are able to discuss not only as a whole but in smaller groups as well (e.g., Krueger and Casey, 2015). Second, whereas the current study focused narrowly on actor groups such as professors, students, and administration to examine collective perceptions of synthetic life sciences, it may be useful, during the emergence and evolution of the ecosystem, to widen this lens to consider if and how the initiatives undertaken in and around the university might also influence perceptions of groups in the local community and government. For the present research, we focused on those with some prior expertise or exposure to synthetic life sciences, given that awareness of this research area has often been low to this point (e.g. Akin et al., 2017). Nevertheless, if synthetic life sciences are to deliver their intended potential for society, and successfully integrate perspectives and aims beyond its heretofore technical and innovation focus (Trump et al., 2020), it will be crucial to integrate the perceptions of the general public, *inter alia*, more directly – with the mixed-methods approach of group concept mapping providing one potential platform for doing so. While the synthetic life sciences have been carefully selected as a representative area for IKA, it will be important for future research to foster comparative discussions of key drivers within other domains of interdisciplinary research.

Beyond methodological considerations, the propositions on how to build legitimacy for emerging IKAs open up ample opportunities for future research. We hope to inspire fellow scholars to further explore the notion of universities as invention ecosystems and provide some guiding questions in the following. The practical implications above already hinted at the need to further define the potential role of the university administration in leading the invention ecosystem. Questions in this context could be what roles and competences are needed and if hybrid roles combining academic and professional tasks could be suitable and attractive. When it comes to specialists with joint expertise in scientific communication and technical competencies, how does one go about attracting or developing those? What might be characteristics of such specialists that can be used to identify them, what conditions might attract them and what processes or support structures need to be in place to develop this joint expertise? The insight that opportunities for science to overcome disciplinary boundaries emerge less as the outcome of natural, internally driven evolution than one much more externally oriented and driven by encouraging more participants to join calls for further elucidation. Especially against the backdrop of legitimacy, what is it that attracts scientists to join an interdisciplinary research environment and are there different influence factors for researchers from different disciplinary backgrounds? Equally important is the early and purposeful engagement of external actors, e.g. by growing the community around the IKA based on extant social ties and prior experience working together. The work of Dedehayir et al. (2022) on roles in innovation ecosystems might provide useful guidance on how such invention teams could be composed. Another interesting question is how different roles contribute in varying ways to the different steps of the legitimation process (Thomas and Ritala, 2022). Another success factor for fostering external buy-in and acceptance is the promotion of benefits for tackling grand challenges such as human health, food supplies, and the environment. This link between the target grand challenge(s) for the IKA and public acceptance deserves more exploration. Especially because the IKA, once instituted, is most likely to be vital to resolving the grand challenge, what are the most effective ways to promote the link between IKA and grand challenges, and the benefits for tackling grand challenges that come with it?

CRediT authorship contribution statement

Chad M. Baum: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nathalie Sick:** Writing – review & editing, Writing – original draft, Conceptualization. **Stefanie Bröring:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Data curation, Conceptualization.

Statements and declarations

The authors declare no competing interests, direct or indirect, which influenced the preparation and presentation of this article or its underlying research. Informed consent was obtained from all participants included in the study, and all data obtained had been de-identified before playing any role in analysis.

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Appendix

Methodology of Group Concept Mapping

Once we have sorting and rating information for all participants, we can use these inputs to generate visual maps elucidating collective representations of actors within the knowledge ecosystem. To do this, we use Global MAX software to create a *binary similarity matrix* for all participants – with the number of rows and columns equal to the total number of statements (Kane and Trochim, 2007). In our case, the sorting information for each participant is represented by a 55 x 55 square binary matrix. If two statements are sorted into the same pile, this cell receives a "1", and a "0" if not. By aggregating individual matrices for all participants, we thus attain a *total square similarity matrix*. This combined matrix retains the 55 x 55 structure of its individual components, but now numbers in the cells reflect the number of participants placing these two statements into the same pile – with a range from 0 to the total number of participants. The higher the value, the more the two statements were perceived to be conceptually similar across all stakeholders (Kane and Trochim, 2007).

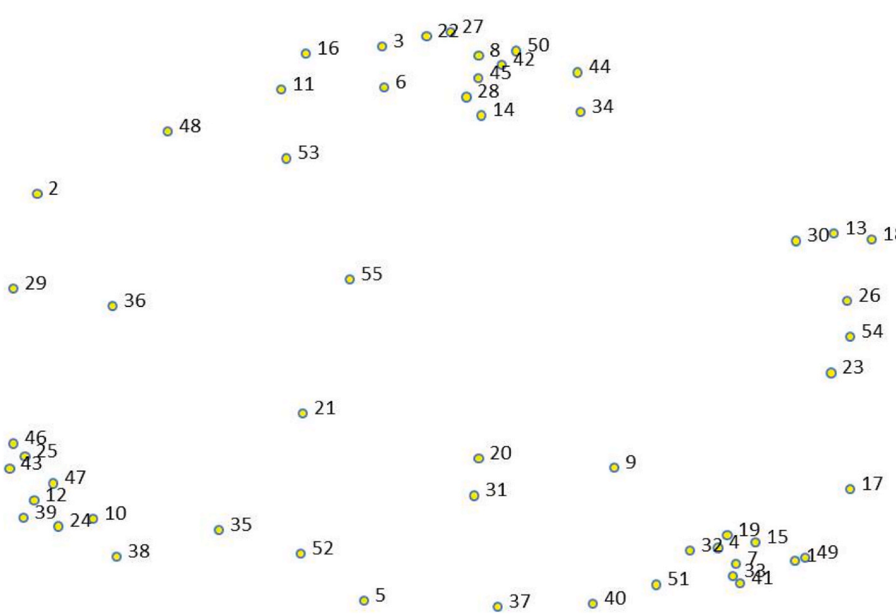

Fig. A.1. Point Map derived from 55 Statements

Next, two-dimensional non-metric multidimensional scaling of the *total similarity matrix* is used to map the statements onto two-dimensional (x, y) space (Kruskal and Wish, 1978; Kane and Rosas, 2018). Each statement thereby takes the form of a point on this map, such that it is possible to view how the statements relate to one another. Having randomized the statements before presenting them to participants, the number bears no relation to the order in which they emerged in the discussion. Multidimensional scaling begins by placing the first point (#1) (see Figure A.1). Then, depending on the degree of conceptual similarity, the second point (#2) is assigned. In our case, #2 was distinct from #1, and so appears far to the left. Meanwhile, #3 is more similar to #2, and thus situated more closely, whereas #4, in the lower right, is more similar, and thus closer, to #1. Having done this for all 55 statements, we attain a point map which provides a visual representation of the total similarity matrix. A stress value, from 0 to 1, is then calculated to assess the reliability of the representation – where lower values reflect a better overall fit between the sorting data and point map. The stress value for our map is 0.1980, indicating a good fit (Kane and Trochim, 2007; Rosas and Kane, 2012). In comparison, a meta-analysis of GCM studies (Trochim, 1993) estimated an average stress value of 0.285 and a 95% confidence interval of 0.205–0.365. Even as a rough guide of the overall fit of the sorting data, we can thus have substantial confidence in the reliability of our (concept) maps.

We can subject the point map to hierarchical cluster analysis in order to group the statements into overarching clusters (Kane and Trochim, 2007; Kane and Rosas, 2018). By successively taking each statement and merging those closest together, until only a single cluster remains, this agglomerative method is able to tease out and reveal those underlying patterns that bond the statements together. Using Ward's algorithm in order to compute the relative distance between statements in Euclidean space (Kane and Trochim, 2007: 98–100),[6] we start with each statement considered to represent its own cluster and, step by step, the points (or clusters) that are most conceptually similar are merged together, resulting in a reduction in the overall number of clusters.

Table A.1
Cluster replay solution

Cluster solution (Total number of clusters)	Merged clusters	Merging Judgment Yes/No/Don't Know
14	1, 2	Yes
13	10, 11	Yes
12	6, 7	Yes
11	4, 5	Yes
10	1, 2, 3	Yes
9	14, 15	Yes
8	8, 9	Yes
7	6, 7, 8, 9	No/Don't Know
6	12, 13	No
5	12, 13, 14, 15	No

Remark The table can be interpreted as follows (e.g. for row one). If results of multidimensional scaling are grouped into 14 clusters (column 1), clusters 1 and 2 merge (column 2), and this is adjudged to be appropriate (column 3).

Hierarchical cluster analysis is then utilized to develop the final cluster map, which highlights and identifies the various clusters (of statements) and their relationships to one another. When it comes to how many clusters to include however, there is no single "correct" number of clusters (Kane and Trochim (2007: 101–103). Following Kane and Trochim (2007), we thus define a minimum (5) and maximum (15) number of clusters on the basis of the group discussion and preliminary examination of sorting data. Having then integrated cluster maps for each solution into a *cluster replay map*, we iteratively adjudged if a merger of clusters makes sense (see Table A.1). If so, we marked "Yes" and moved on to the next decision; if not, we marked "No" or "Don't Know". By identifying the inflection point where "Yes" turns into "No" or "Don't Know", we selected the 8-cluster solution to be optimal. Indeed, as a 7-cluster solution entailed merging two clusters that were rather distinct, in terms of conceptual meaning and the distances between their respective statements, this offered confirmation for the 8-cluster solution.

Cluster names emerge primarily from the descriptions participants assigned to piles of statements. The more often a name is used for a group of statements, the more likely it will be assigned to the cluster. Indeed, most of the clusters attained their name in this way, notwithstanding the occasional addition or deletion of a word or two. The only exceptions are related to "Reservations of the General Public" and "Everyday Relevance". The most usual labels for the first were: "External influences", "Public fear", "Prejudices" and "Societal reservations (and concerns)". The new label combined these to highlight the underlying statements (see Table 3). More challengingly, initial suggestions for "Everyday Relevance" included "Political considerations", "Worries", "Regulation", and "Self-protection", but none of the statements seemed to capture these features. "Everyday Relevance" thus represents a kind of implicit category not precisely intended by any one individual, but which emerged at the cross-roads of their other clusters. However, the fact that its constituent statements display conceptual links to the necessity of the synthetic life sciences having concrete and practical impact for clients and consumers does impart a particular importance to its unexpected emergence, indeed, at the core of the cluster map.

Data availability

The data that has been used is confidential.

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[6] To be specific, Ward's algorithm seeks to minimize the sum of the squares of the distances between all statements in the two (hypothetical) clusters which we are determining whether to merge together (see Kane and Trochim, 2007).

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