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Boundary-spanning by design? Policy-induced innovation collaboration in the German bioeconomy

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ABSTRACT

In 2019, the German government introduced a new policy to spur field-spanning innovation synergies in the bioeconomy. The so-called 'Innovation Space' defines a funding umbrella around a specific bioeconomy subfield and delegates authority of decision-making on new grants and members to the initially funded consortium. In this paper, we explore the extent to which one Innovation Space focusing on bio-based textiles experienced knowledge cross-fertilization between distinct projects. We propose a typology of boundary-spanning knowledge relationships and apply a mixed relational methods approach to empirically assess the potential for knowledge cross-fertilization and, hence, policy-induced collaboration in the textile bioeconomy. Despite its recent emergence, we find incidence of boundary-spanning learning relations across projects and sectors (science–industry) since inception of the Innovation Space. Members with permanent or temporary geographical co-location, and those receiving referrals from colleagues, were more likely to engage in knowledge exchange than other members. Project managers were involved in two-thirds of boundary-spanning, whereas similar relationships between only technical members were rare. Additionally, analysis of network robustness shows that learning across project boundaries was vulnerable to already low membership fluctuation. The findings suggest that Innovation Spaces are a policy instrument that fosters knowledge cross-fertilization beyond the confines of bounded projects.

1. Introduction

The contemporary challenges of climate change, scarce fossil resources, and the severe environmental impact of continued growth in industrial production and consumption call for a transition from fossil economies to more sustainable systems of production and consumption (Geels, 2019; Köhler et al., 2019; Proestou et al., 2024; Truffer et al., 2022). In this context, the bioeconomy assumes an important role in the global quest for sustainability transitions (Losacker et al., 2023; Wohlfahrt et al., 2019). The bioeconomy seeks to tackle the environmental challenges by integrating biotechnologies into the production process and, at the same time, to promote economic development (Sanz-Hernández et al., 2019). Generally, all economic activities based on biological processes and renewable resources can be considered as part of the bioeconomy (German Bioeconomy Council, 2018). In practice, the bioeconomy covers a wide array of technologies, markets, and applications (Golembiewski et al., 2015), ranging from traditional agriculture and forestry to high technologies, such as life sciences and biosynthetic materials (Hoffmann & Glückler, 2023a).

Because of its potential to contribute to sustainability transitions (Truffer et al., 2022), governments in more than 50 countries have created support policies to foster bioeconomy research, and to implement strategies for research and development (Prochaska & Schiller, 2021; Sanz-Hernández et al., 2019). These measures range from loosely communicated visions and recommendations to long-term project funding worth millions of euros (BMBF, 2016; Proestou et al., 2024). The bioeconomic sustainability transition benefits from collaborative innovation across the boundaries of knowledge and technology domains (Mariani et al., 2022). Boundary-spanning learning promotes innovation, which is why a central component of most funding measures is to support knowledge exchange between stakeholders of different knowledge domains and co-creation activities (Prochaska & Schiller, 2021; Proestou et al., 2024). Despite their widespread implementation, there is limited empirical evidence on how these measures actually promote

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learning across the boundaries of organizations, projects, and knowledge domains (Bednarz & Broekel, 2019). Consequently, innovation has sometimes been addressed by unreflected policy interventions (Hammond et al., 2022). This black box of policy effectiveness motivates this paper to explore and assess the association between a new instrument for policy-induced collaboration and the emergence of knowledge relations, which effectively span the boundaries of organizations and projects.

In response to efforts of inducing collaboration, the German government has introduced a new policy instrument to precisely enable boundary-spanning innovation synergies in the bioeconomy. The so-called 'Innovation Space' policy defines a funding umbrella dedicated to specific subfields of the bioeconomy, where the government delegates authority of decision-making to an initial consortium of research-intensive corporations, universities and other research organizations. This consortium is authorized to admit new members, and to develop and approve multiple new grants and projects without additional external reviews. At the core of the innovation space lies a project network composed of individual projects, each with specific objectives. While each project is managed by project managers, a central Project Management Office (PMO) provides support to all projects, particularly with regard to administrative responsibilities. In the context of this innovative funding policy, we explore the extent to which knowledge cross-fertilization across the many projects emerges, and we examine the conditions that support their emergence.

The paper proceeds as follows. Section 2 discusses key ideas around the social dilemma of innovation collaboration, policy-induced collaboration and boundary-spanning. Section 3 reviews the literatures on economic geography and social networks to identify three mechanisms claimed to support the creation of network relations: permanent geographical proximity, temporary geographical proximity, and networked reputation. In addition, the section presents a typology of boundary-spanning relationships. Section 4 discusses the design features of the 'Innovation Spaces', and reports the research design as well as the methods used for primary data collection, construction of measures and empirical analysis. In Section 5, we present the findings of our analysis suggesting that Innovation Spaces have actually enabled the emergence of synergies by way of learning relations that reach across the boundaries of projects and knowledge domains. In Section 6, we draw a few conclusions about how to actively support cross-fertilization in the emerging field of the bioeconomy.

2. Innovation collaboration in the bioeconomy

2.1. The social dilemma of innovation collaboration

As Hayek has forcefully maintained, "the economic problem of society […] is a problem of the utilization of knowledge not given to anyone in its totality" (Hayek, 1945: 519–520). Accordingly, innovation depends on the combination of distributed knowledge by way of recombination. To enhance the recombination of distributed knowledge, actors benefit from two aspects: absorptive capacity and collaboration. Firstly, *absorptive capacity* is the ability to spot new knowledge in the environment, recognize its utility for the home domain of knowledge and translate this knowledge into the innovation process (Cohen & Levinthal, 1990). Secondly, *collaboration* refers to interactive learning and the co-creation of knowledge. Hence, collaboration and access to new knowledge through cooperation potentially facilitates synergies for innovative recombination (Owen-Smith & Powell, 2004).

The collaborative pursuit of innovation offers opportunities and threats, potentially locking collaborators in a dilemma. On the one hand, collaboration across organizational and domain boundaries improves the opportunity for discovery and invention by way of sharing and combining complementary, be it related or unrelated (Frenken et al., 2007; Boschma, 2017) knowledge, and by lowering individual costs due to cost-sharing in collaborative efforts (Benhayoun et al., 2021; Sørensen & Torfing, 2011; Torfing, 2019). Collaboration is a safeguard, for instance, against the "not-invented-here syndrome" (Katz & Allen, 1982). In addition, collaboration improves the potential effectiveness of innovation, for example, by assessing whether new solutions can be acquired from the market or by collaboration (Dahlander & Gann, 2010; Gallaud, 2013).

On the other hand, collaboration implies the risk of opportunism. Collaborators may adopt strategies of free-riding, i.e. limiting or even withholding important input in the collaborative project (Nordhaus, 2015), or of privatizing the gains from cooperation, e.g. through unauthorized imitation or appropriation of the outcomes of collaboration (Glückler & Hammer, 2017). Altogether, Gallaud (2013) highlights three key risks of collaboration: collaborators may become competitors after the joint venture, the internal creativity of firms may be harmed through negative spillovers, and conflicts over ownership rights can occur. In addition to these general risks, innovation collaboration with universities and other public research organizations leads to public leakage of new knowledge, which by way of publication becomes state of the art and impedes private innovators to claim and reserve intellectual property rights (Owen-Smith & Powell, 2004).

Empirical research has demonstrated that many firms, especially SMEs, either face problems in reaping the benefits of networking or deny collaborating with other organizations altogether (Caloghirou et al., 2006; Glückler, Panitz, et al., 2020). To date, research on the design and governance of organized multilateral networks is still scarce (Provan & Kenis, 2008). In this context, one of the burning questions is how actors can reconcile the tension between the benefits and the risks of boundary-spanning collaboration to jointly reap the gains of cooperation in innovation. Answers to this question require knowledge about how to build collaborative relationships as well as how to enact effective governance of the network of collaboration (Lopes & Farias, 2022). Although contracts are a good way of formalizing agreements among partners, it is impossible to anticipate and regulate the potential imponderability entailed in a process of multilateral collaboration (Macaulay, 1963; Blumberg, 2001). Hence, continuous governance is indispensable to build and sustain effective collaboration while reducing the risks of opportunism (Lopes & Farias, 2022). Governance can be defined as a process of coordination among actors that are interdependently linked around a collective problem, in pursuit of a consensual objective (Glückler, Herrigel, et al., 2020). In this context, policy interventions aim to resolve the social dilemma of innovation collaboration by establishing governance forms and procedures that support collaborative innovation (Sørensen & Waldorff, 2014).

2.2. Policy-induced collaboration

Policies in support of innovation have a comparatively long history (Tsipouri et al., 2006), have addressed a variety of goals, and they have made use of different tools and measures to pursue them (Sørensen & Waldorff, 2014). Extant research supports the positive effect of policy interventions on collaboration and innovation (Anić, 2017; Bednarz & Broekel, 2019; Schütte, 2018), and suggests that they can direct scientific and economic focus on specific topics or problems, strengthen the intersection between science and industry (Kochenkova et al., 2016) and spark cross-border cooperation, such as technology transfer (Feldman et al., 2012).

The framework conditions of policy instruments depend on the composition of the stakeholders (Boschma, 2005; Proestou et al., 2024; Provan & Kenis, 2008). Whereas in the private business sector, the protection of knowledge and intellectual property means competitive advantage, knowledge is being made broadly available in academia to advance the frontiers of the scientific state of art (Owen-Smith & Powell, 2004). And regarding government organizations, it is the geographically restricted responsibilities and interests that structure and limit exchange (Dutta et al., 1999).

In economic geography, cluster approaches have been one way of understanding and promoting collaboration between organizations (e.g. N'Ghauran & Autant-Bernard, 2021; Turkina & Van Assche, 2018). In line with cluster thinking, co-located R&D departments are expected to benefit from agglomeration advantages through related and complementary economic activities (Graf & Broekel, 2020). In addition, funding approaches seeking to strengthen the third mission of science are being implemented (Bortagaray, 2009; Nelles & Vorley, 2010; Compagnucci & Spigarelli, 2020). Moreover, in suggesting the promotion of productive university-industry-government relations (Leydesdorff & Etzkowitz, 1998; Viale & Campodall'Orto, 2002; Viale & Pozzali, 2010), the Triple Helix approach allows to exert both indirect and direct influence on rule makers and rule-making (Etzkowitz, 2018).

The key objective of most policy interventions is to enhance knowledge sharing between individuals and organizations, sectors and regions (Prochaska & Schiller, 2021; Proestou et al., 2024; Silvia, 2018a). This is often achieved through what is known as *boundary-spanning*: processes and activities that facilitate the flow, absorption, and co-creation of knowledge across communities, domains, and organizational boundaries (Teigland & Wasko, 2003). The two central strategies used in policy designs to forge boundary-spanning knowledge sharing are, first, financial incentives to engage in collaboration, measures to reduce transaction costs, enforced government mandates, and reputation-based programs (Gillenwater, 2012). The second strategy is to focus on the governance of collaboration by managing how knowledge is shared and utilized among participants to ensure effective cooperation and prevent misuse or loss of valuable information (Brunet, 2019).

Empirical evidence suggests that diversity among collaborative actors enhances the potential for innovation (Burt, 2004; Corrocher & Lenzi, 2022; Walrave et al., 2024). Spanning different knowledge domains fosters innovation, because recombining diverse knowledge components increases the opportunity for creating new knowledge and innovation (Burt, 2004). Knowledge diversity positively influences innovation *activity* (Corrocher & Lenzi, 2022) and innovation *performance* (Walrave et al., 2024). In science and engineering domains, teams comprising members with diverse expertise were found more likely to generate original contributions (Li & Zheng, 2025), and a broad technological knowledge base has been associated with increased impact of technological innovations (Rosenzweig, 2017). However, increasing size and diversity of a network incur the challenge of managing the complexity of potential synergies as well as the risk of exposure to opportunism (Carlile, 2002).

As an emerging field (Proestou et al., 2024), the bioeconomy is precisely characterized by considerable heterogeneity and diversity of knowledge and technologies, with often disconnected evolutionary trajectories in the past (Hoffmann & Glückler, 2023a). Innovation in such heterogenous and partly disconnected fields requires mechanisms for cross-fertilization of knowledge beyond the confines of individual knowledge domains, sectors, markets and applications. That is why both the need of knowledge domain level collaboration (Gray, 1985) as well as policy interventions are a cornerstone of the bioeconomy (El-Chichakli et al., 2016). The bioeconomy has emerged as both a modern economic sector and an analytical concept (Adamowicz, 2017). It serves as a vision for transformative change (Proestou et al., 2024) and an umbrella for scientific, technological, and policy initiatives. Yet, its broad and overlapping scope creates conceptual and identity ambiguities (Hoffmann & Glückler, 2023a). Given these blurred sectoral boundaries, simple economic calculations, such as those used in Germany to evaluate the output (Efken et al., 2016), are insufficient. More precise measurement approaches are needed to distinguish outputs from related sectors (Mittra & Zoukas, 2020). Innovation in the bioeconomy is foremost collaborative innovation (Bröring et al., 2020), and it is most wanted to help advance climate adaptation and environmental protection by shifting the economy from fossil to renewable resources. It is a field that promotes innovation in particularly novel areas that require recombining knowledge from diverse and often disconnected fields of technology (Hoffmann & Glückler, 2023a). Furthermore, as breakthrough innovations imply high risks of failure, collaboration is an appropriate way of concentrating expertise while at the same time sharing this risk among various partners or absorbing it through distributed funding schemes (BMBF, 2016; Bröring et al., 2020; BMBF & BMEL., 2020).

Most frameworks for the evaluation of innovation support policies have relied on ex-post assessments of collaborative research and boundary-spanning learning (Blackstock et al., 2007; Hegger et al., 2012; Walter et al., 2007). Ex-post assessments are subject to two problems: first, in many cases there is no clear definition of the intended outcomes and responsibilities, which makes it difficult to trace exactly what was planned by whom and to what extent boundary-spanning contributed to this end (Silvia, 2018). Moreover, the impact of boundary-spanning activities tends to be subtle and may take long time before becoming manifest (Chowdhury et al., 2016). Hence, it is not always clear if the effect of boundary-spanning activities has already become measurable. A second problem is the difficulty of comparing assessments across policies because of differences in objectives, theoretical foundations, measures and the ways in which criteria were operationalized. As a result, many assessments still rely on aggregate data and draw conclusions based on proxies of knowledge exchange (De Iudicibus et al., 2024; Tassinari et al., 2021; Zhao et al., 2024).

Assessing boundary-spanning activities in the bioeconomy presents a particularly complex challenge due to the high degree of diversity within the domain, and the involvement of numerous heterogeneous actors (as discussed in the previous sections). Aggregated assessments based on, for example, public information on the division of labor during the project, as well as co-publications and patenting, would not reveal any indication of how individuals actually learned from one another, what connections they established and if knowledge sharing did span domain boundaries to successfully turn synergies into innovations.

2.3. A network approach to knowledge cross-fertilization

To overcome the previously discussed limitations, we engage in an in-vivo social process of collaborative innovation rather than looking at ex-post-factum evidence, and we zoom in on the level of individuals and their social relations at the micro level. Adopting a relational perspective and employing methods of social network analysis, we aim at collecting robust data on knowledge sharing at the actor level as well as a precise analysis of drivers of boundary-spanning learning. This granular empirical approach, in combination with organizational and project affiliations, makes it possible to distinguish planned collaboration (within funded projects) from the additionality of across-project learning and collaboration. Although our focus on learning relations among individuals is not a final measure of innovation output, we view these relations as a key mechanism for subsequent innovation (Proestou et al., 2024).

While the importance of cross-fertilization of knowledge across organizational and project boundaries is widely acknowledged, there is still little empirical evidence on how such cross-fertilization can be actively supported. Understanding the mechanisms and conditions that favor productive boundary-spanning is therefore crucial to support innovation ecosystems in the bioeconomy. The following drivers for collaboration at actor level are identified and evaluated in the context of ongoing innovation collaboration.

2.4. Drivers of boundary-spanning knowledge sharing

Any activity that is a result of a policy intervention and that would not have come about without it, is called an additionality (Gillenwater, 2012). We explore the additionalities or conditions that effectively support the appearance of boundary-spanning knowledge sharing. Although we lack systematic information on prior linkages between individuals, we make the assumption that boundary-spanning relations were created after the inception of the Innovation Space. This assumption is supported by our questionnaire, which explicitly asked respondents to report relationships that developed during the course of the projects (Section 4.2) as well as by our personal experience of being founding members of the Innovation Space. However, since we were unable to collect dyadic-level data on the exact timing of relationship formation, we concede that a residual uncertainty remains. Reviewing the literatures in economic geography and social networks, we identity three conditions that have been claimed to enable the creation of new knowledge links in networks: geographical co-location, temporary proximity, and networked reputation.

2.5. Geographical co-location

Research in economic geography as well as in social networks consistently suggests that spatial agglomeration and *geographical co-location* enhance the creation of new contacts and relations between people and organizations (Boschma, 2005; Balland, 2012; Ferrary, 2003; Giuliani, 2013; Giuliani et al., 2019; Glückler, 2007; Healy & Morgan, 2012). Broekel and Boschma (2012), for instance, analyzed the knowledge network of the Dutch aviation industry and found that geographical proximity was a significant driver of network formation. However, they also argued that spatial proximity was not the only and not necessarily the central explanatory dimension in the formation of new knowledge relations. Instead, they showed that the kind of knowledge, the societal embeddedness and the structure of the organizations were important, too. Accordingly, we expect that boundary-spanning relations are more likely to appear among co-located than among spatially distributed members in the *Innovation Space*, especially if the actors are affiliated with different knowledge domains, and organizations, a situation called 'local brokering' (Glückler, 2007). Geographical co-location is to be treated as an ex-ante condition to the implementation of a project, such as the *Innovation Space*. It is unlikely to assume that organizations change their location as a consequence of receiving funding in the Innovation Space. Instead, the German textile industry is spread across many locations in Germany, with some clusters in a few regions, including textile weaving in North Westphalia and Bavaria, or textile processing in Baden-Württemberg (Brenner, 2006). As a consequence, we treat geographical co-location as an external condition to the network of organizations rather than a mechanism for network formation in the context of this impact assessment.

2.6. Temporary proximity

In contrast to permanent co-location, individual mobility can be used as a purposive mechanism during the course of a project to organize *temporary proximity* between otherwise remote individuals to create exchange and new social ties (Torre, 2008). Accordingly, *temporary proximity* has been a proven technique in project governance (Torre & Rallet, 2005) as well as in the rise of the entire industry of business tourism, trade fairs, and conferences (Bathelt et al., 2014). It has been shown that innovation and knowledge creation benefit from face-to-face interactions (Autant-Bernard et al., 2007; Ponds et al., 2007). This is particularly true for the exploration and sharing of tacit knowledge (Torre, 2008; Zander & Kogut, 1995). As a deliberate element in the governance of the *Innovation Space*, the administrative unit of the project management office (PMO) may enhance the emergence of boundary-spanning relationships by organizing different types of events, including conferences, workshops, insight session, pitches, or real-labs, where members come together for personal exchange. Accordingly, our second conjecture is that boundary-spanning relationships are more likely to appear among actors who frequently attend the same events.

2.7. Networked reputation

Personal referrals, a practice called *networked reputation* (Glückler & Armbrüster, 2003), are a way of transferring the positive reputation gained through experience by a direct contact to a trusted new contact. Networked reputation has been shown to be a key mechanism for endogenous network evolution (Hoffmann & Glückler, 2023b). A well-known example from the social network literature that relies on networked reputation is the behavior of tertius iungens (Obstfeld, 2005): a broker uses their position to connect two unconnected actors. This closes the structural holes around the broker, and at the same time opens new structural holes in the neighborhoods of the newly connected actors. The networking of reputation and the creation of new links shifts the advantage of the individual to the advantage of the network, and so propels the exchange of ideas and the co-creation of new knowledge. This reconnection only works if there is sufficient trust between the actors in the network (Obstfeld, 2005).

Trust, in turn, emerges in relational stability and reciprocal exchange in informal settings, both of which have been shown to produce and reinforce trust (Molm et al., 2009). As such, trust is treated as a foundational precondition for successful reconnection in networked settings. Empirical research has shown that networked reputation and tertius iungens behavior increase the innovation rate of groups (Brändle et al., 2024; Llopis et al., 2021; Xu et al., 2023). In the context of this study on boundary-spanning in the bioeconomy, individual members as well as all the entities involved in the governance of the projects (project manager) and the *Innovation Space* (PMO) may actively create linkages between disconnected members by word-of-mouth and personal referrals. Accordingly, we conjecture that actors reporting new contacts through referrals by the governance body are more likely to engage in boundary-spanning exchange than those who did not. Organizing temporary proximity among stakeholders provides a social context that potentially enhances the emergence of boundary-spanning knowledge sharing, e.g. by way of referrals from project peers or from external governance actors (Torre, 2008; 2025).

Each of the three mechanisms and conditions – permanent proximity, temporary proximity, and networked reputation – has empirically been shown to enhance the creation of new relationships and to spur innovation. In this study, we are particularly interested in the creation of those knowledge links that go beyond the boundaries of projects to facilitate cross-fertilization among disconnected fields of research. We therefore propose a typology of boundary-spanning relations in the following section to enable a meaningful categorization and for empirical assessment. Empirically, we will take a focal interest in whether boundary-spanning relations, once observed, are consistent with the three mechanisms and to what extent project governance can support their emergence.

2.8. A typology of boundary-spanning relationships

We propose a typology of boundary-spanning network ties (Fig. 1): it distinguishes three levels, ranging from relations *within an organization* (type-1), relations within a project but *across organizations* (type-2), to relations *across projects* (type-3):

Type-1 intra-organizational ties. In a project (Fig. 1, *large circles*), individual members (*nodes*) share knowledge with and learn (*black ties*) from other colleagues within their organization (squares) in pursuit of the completing the goals and tasks assigned to a project. These ties are common and well-studied, yet they are of less interest in our study because intra-organizational collegiality tends to offer less potential for the recombination of disconnected knowledge domains than relations than span boundaries of organizations and projects. Technically, intra-organizational ties include those relations among colleagues from one organization who are assigned to different projects. Hence, we could further distinguish type-1a ties (intra-organizational within a project) from type-1b ties (intra-organizational across projects).

Type-2 inter-organizational ties within a project. A project (Fig. 1, *circles*) may include different organizations (*squares*), whose individual members (*nodes*) span the boundaries of their own organization to share

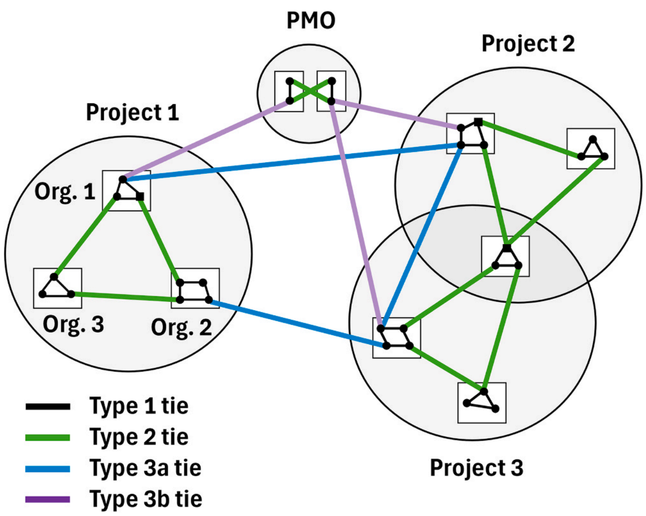

Fig. 1. A typology of boundary-spanning learning ties.

knowledge (*green ties*) with individuals of another organization in pursuit of the project goals and tasks. Type-1 and type-2 relationships are often an immediate consequence of the planned and expected interactions for the processing of defined work packages and for reaching milestones that constitute the mandatory backbone of innovation collaboration.

Type-3 inter-organizational ties across projects. One of the built-in objectives in the design of the funding program of the *Innovation Space* is to facilitate the cross-fertilization of knowledge across different projects. Accordingly, we define knowledge sharing ties between members across different organizations and across projects as type-3 relationships (*red and blue ties*). Unlike type-2 relationships, the interaction between individuals across different projects is not purposively designed in any work package, and, hence, can be considered an unplanned synergy. These genuine interactions reach beyond the project horizon, and when being acknowledged as effective sources of knowledge, these interactions offer the potential to foster cross-domain innovation. Due to the successful boundary-spanning of unrelated knowledge from different contexts, type-3 relations have the ideal prerequisites for the recombination of knowledge by exploiting spillovers and synergies.

In the specific context of this study, the *Innovation Space* 'Biotexfuture' includes two non-technical projects, i.e. the governance PMO and a social science project for accompanying research. Hence, we distinguish the two sub-classes of type-3 ties: type-3a ties indicate *technical* boundary-spanning relations (*blue ties*) between individuals across organizations and technical projects. Technical projects are dedicated to the innovation of new biosynthetic products, procedures, technologies or services. In contrast, type-3b ties denote *non-technical* boundary-spanning relations (*purple ties*) that involve any members of either the PMO or the accompanying social science project. The central governance unit, PMO, mainly interacts with the project manager of each of the projects (*filled-in square*) to coordinate activities, share information, oversee the reporting and assist with expertise when needed. Type-3b relationships can be seen as successful boundary-spanning activity by governance actors in the *Innovation Space,* yet they are not likely to produce technical innovations.

Due to the specified project goals and outcomes, project members are expected to focus on completing their tasks according to the project plan. Due to the planned workload, type-1 relationships as well type-2 relationships are likely to emerge according to the work plan. Conversely, because interaction across projects is not contained in any project workplan ex-ante, type-3 relationships are less likely to emerge, even though the BMBF has designed the *Innovation Space* precisely to increase the serendipity of exchange between projects in a common domain of research. In light of these framing conditions, we pose the following research questions:

(1) Does the *Innovation Space* convey type-3 boundary-spanning learning?
(2) How robust are boundary-spanning ties in such collective innovation settings?
(3) Is the emergence of boundary-spanning ties associated with geographical co-location, temporary proximity, and networked reputation?

3. Methodology

3.1. Public policy innovation: the innovation space

In 2019, the German Federal Ministry of Education and Research launched the Bioeconomy *Innovation Spaces* funding instrument, aiming "to utilize research results more extensively than before and to initiate innovations that will become building blocks of a process of change for society as a whole in support of the bioeconomy" (BMBF, 2016: 1). Within this framework, stakeholders from industry, science and government are brought together to engage in innovation collaboration over a period of up to five years. The combination of four features sets the *Innovation Spaces* apart from conventional innovation policies:

First, the *Innovation Space* empowers the sponsored organizations within the bioeconomy domain to define their research priorities and projects themselves. Because the bioeconomy is a vast, imprecisely confined and transversal technology field that cuts across almost all sectors of the economy (BMBF & BMEL., 2020), the BMBF issued a call for multiple proposals and finally decided to support a total of four *Innovation Spaces*, including bioeconomic research on textiles, foods, maritime and metropolitan bioeconomies. The Ministry as well as industry corporations co-fund each *Innovation Space* up to an aggregate of 20 million euros over the period of five years (BMBF & BMEL., 2022b).

Second, the *Innovation Spaces* specify, develop and approve new projects and partners on their own. The formal governance structure of an *Innovation Space* includes the delegation and decentralization of authority. Each *Innovation Space* is authorized to independently select and develop new projects, and accept new partners, conditional upon their compliance with the formal funding regulations. This delegation of authority allows the *Innovation Space* to dynamically respond to emerging opportunities and to evolve along an adjustable innovation trajectory (BMBF, 2016). Each project has a project manager (PM) who ensures the successful completion of the project.

Third, a central project management office (PMO) is established that assumes administrative and coordinative tasks and processes for its members. The PMO mediates between the project sponsors and the project manager of each funded project, resolves conflicts and takes measures to improve cooperation, such as organizing events and meetings. All projects must report to the PMO and to the project sponsor on a regular basis. In addition, the PMO collects regular progress reports to be passed on to the project sponsor (BMBF, 2016). In addition to the governance bodies (PM, PMO, and a steering committee) and the coordinated activities (reports, events, etc.), funded partners sign contracts at different levels: at the level of the *Innovation Space*, each funded member signs the innovation alliance agreement (*Innovationsbündnis*), and all extant members have to agree with every new applicant before joining the alliance.

Fourth, the *Innovation Spaces* create an opportunity space for and promote the emergence of synergies and cross-fertilization. The notion of the *Innovation Space* refers to a cluster of collaborative projects in which each project strives to achieve defined goals within a specific sector of the bioeconomy. These project goals must be aligned with the overarching goals of the *Innovation Space* in order to facilitate spillovers, synergies and additional, unplanned innovation potential. The *Innovation Space* aims to enable a culture of innovation that generates new forms of collaboration, creating open spaces where creative research and development work is facilitated, and cooperative research can be more easily initiated and realized (BMBF, 2016).

At the level of the funded projects, members sign cooperation agreements, which set contractual rules for intellectual property and commercialization. To enhance interaction between science, business and society, researchers from both, academia and corporate R&D, receive funding to exchange ideas and get mutual access and early insight into technological developments. Both stakeholders are expected to communicate broadly and reach out beyond the *Innovation Space* to the public (BMBF, 2016; 2019).

In this paper, we focus on one *Innovation Space* dedicated to converting the textile value chain from petroleum-based to bio-based (BMBF & BMEL., 2022a). Having started in 2019 with four projects, it grew to eight projects, including 80 individuals from over 70 organizations by 2023. It includes two lead organizations and numerous small and medium-sized companies working together with research institutes within the textile bioeconomy (BMBF, 2022). Individual projects pursue the production of sports textiles from microalgae; the development of bio-based alternatives from already available resources for textile applications; bio-based coatings for fibers in high-performance textiles; sustainable artificial turf systems made from bio-based polymers; elastic textile fibers based on CO_2; degradable geo-textiles; and materials from fungal mycelium.

The *Innovation Space* operates on three levels. First, within each project, partners engage in inter-organizational collaboration to implement their funded work plans and achieve the project goal. Second, at the *Innovation Space* level, the PMO facilitates and promotes exchange between the projects by organizing different types of online and offline events and by sharing information across the *Innovation Space*. In addition, a steering committee provides strategy recommendations and makes final decisions on assuming new projects and partners. Third, the PMO and steering committee encourage all partners to reach out to the public and actively communicate their research and its findings to consumers.

3.2. Case study and data collection

We adopt a network perspective, which is recognized to be useful for the analysis of collaboration at the actor level (Cantner et al., 2010; Glückler, 2007; Ter Wal & Boschma, 2009). De Iudicibus et al. (2024), for instance, used methods of social network analysis to assess the effect of regional innovation policies in Italy on network affiliation. Drawing on a two-mode participation network (firms jointly involved in projects), they converted the data into one-mode co-participation network information (firms are partners in the same project) to interpret the information as a collaboration network. Yet, having been affiliated to the same project does not necessarily mean that all partners collaborate among each other or that they even know all the other partners. Therefore, although affiliation networks are interesting proxies for actual collaboration, they fail to observe collaboration at the level of individual relations. The challenge of appropriate assessments of collaboration rests on stakeholder and framework conditions, as well as on the authenticity, validity, coverage and granularity of the data, and the quality and validity of the concepts and measures defined ex ante.

The empirical subject of the case study is an *Innovation Space* focusing on biobased textiles. At the time of the study, it included nine projects, of which seven were technical projects, the project management office and a social science project for accompanying research (Table 1). The authors were part of the accompanying research in the *Innovation Space* and pursued the goal of investigating the innovation collaboration. Three technical projects had been involved since the beginning in 2019, whereas the others joined later. All projects were located in the textile bioeconomy field, and many covered the complete value chain of a product, albeit with different goals, including new bio-based products, technologies and applications. One project, for instance, explored the technical feasibility of producing textile applications, such as sports shoes, from algae. Project partners were responsible for different stages of the process, including algae cultivation and extraction, polymer synthesis, yarn development, and final application development. At each stage of the value chain, the quality of the intermediate products is assessed and benchmarked against the performance requirements of sports textiles. The project culminated in the creation of a demonstrator, accompanied by relevant measurements and insights gained throughout the entire value chain.

The diversity of the interacting domains is best described in terms of the core competencies of the organizations involved. Altogether, 39 organizations with a total of 130 people were part of the *Innovation Space* at the time of conducting this study.

Because of the diversity of participating organizations (Table 2), we sorted them into seven different categories that can be aligned along the value chain of the (bio)textile industry: At the beginning of the chain, (1) textile research/consulting ($n = 2$) advise on raw materials and intellectual property; (2) one organization deals with the cultivation/processing of algae as a bio-based textile raw material; (3) Textile development ($n = 15$) includes polymer development, fiber production and yarn production; The fourth category includes application/product development ($n = 8$), which, among other things, deals with textile for sportswear, geo-textiles, cars, medical applications, football turf, etc.; In addition to the organizations that conduct (5) product testing ($n = 1$) and in some cases (6) installation of products (underground construction; $n = 1$), finally, there are organizations that conduct (7) accompanying research ($n = 8$), including consumer research on acceptance of biobased products.

For a comprehensive understanding of the *meanings* and the *structure* of boundary-spanning exchange (Glückler & Panitz, 2021), we adopt the

Table 1
Descriptive statistics of the biotextile Innovation Space.

Project level	Frq.	Organization level	Frq.	Number of members	Frq.
Total number	9	Number of organizations	39	Number of Members	130
Organizations per project	2–12 (⌀ 6,1)	Number of projects per organization	1–7 (⌀ 1,41)	Number of active Members	80
Duration (years)	1–4 (⌀ 2,7)	Number of Members per organizations	1–18 (⌀ 3,3)	Number of respondent Members	65
Individuals per project	3–35 (⌀ 16,4)			Members in multiple projects	17
Project co-memberships	1 – 4 (⌀ 1,2)				

Table 2
Organizations in the biotextile Innovation Space by knowledge-domain.

Knowledge Domain	N	Knowledge Sub-Domain	N
Textile Research/ Consulting	2	Database	1
		Textile Research	1
Feedstock Cultivation/ processing of bio-based textile raw materials	1	Cultivation and extraction of Algae	1
Textile Development	15	Polymer	5
		Fiber	4
		Yarn	6
Application/ Product development	8	Clothing/ sportswear	2
		Geo-textile	2
		Car	1
		Medicine	1
		Food packaging	1
		Soccer turf	1
Product Testing	1	Analysis	1
Implementation	1	Construction	1
Social Science	8		

mixed methods approach of SONA, Situational Organizational Network Analysis (Glückler, Panitz, et al., 2020). This methodology combines interviews with participant actors, such as project managers and team members, and a formal network analysis to map the structure of collaboration in the given context. In this paper, the focus is on the survey, while the interviews are used for validation. The study focuses on relationships between actors across organizational and project boundaries at the actor level.

First, we conducted preliminary interviews with all PMO members and all project managers to understand (a) the organizational and social structure of the *Innovation Space*, (b) the challenges of an organizational network in its spatial and temporal context, and (c) the requirements and objectives of collaborative innovation. We drew on these conversations to develop a detailed interview guide for subsequent in-depth interviews with project members.

Second, we conducted 14 interviews with governance actors, including members of the central PMO as well as managers of the individual projects. We opted for a semi-structured approach to maintain comparability while retaining flexibility in capturing the interviewees' individual perspectives (Flick, 2014). The interviews were conducted between August and November 2022 in the native language of the interviewee (German or English), lasted about an hour, and apart from four online interviews, were conducted on site at the interviewees' offices. Transcription was facilitated through a semi-automated process using the 'whisper' software (Wollin-Giering et al., 2024), and, following the recommendations by Dresing and Pehl (2015), focused on content while disregarding non-verbal elements or filler words. We coded the transcribed interviews using fixed criteria and a category system (Rädiker & Kuckartz, 2019), using MAXQDA (VERBI Software, 2019). The categories served as a basis for qualitative content analysis (Flick, 2014; Mayring, 2015), which itself informed the subsequent survey design. Although the interviews are not at the core of the analysis presented in the remainder of this paper, they have been important to understand context, the nature of exchange and activities in the *Innovation Space*.

Third, we conducted a network survey among all members of the *Innovation Space*. The survey achieved a response rate of 86 % of all members. Participants were able to nominate other people who had previously worked on the projects, which is why so many people were nominated but did not take part themselves. To capture interpersonal relations of knowledge sharing, we provided respondents with a complete name list of all 150 members of the *Innovation Space*, being arranged by organization and project affiliation. In an initial step, people were asked to indicate all contacts "*with whom they had talked before*".

Providing the full list of members was preferable over the alternative of a name generator because recalling names of cursory contacts can be challenging but is often alleviated through contextual information, such as organizational or project affiliations. In the following step, we asked respondents to select from the reduced list of contacts "spoken to" those individuals from whom they had adopted useful knowledge, by asking (Glückler, 2014; Glückler & Hammer, 2017): "*who has helped you solve work-related problems or build new knowledge in the project*".[1] In addition, the survey included items addressing the members' relationships with other project participants, respondents' project affiliations, their skills and engagement in the project, their attendance of project events, and their expectations and experiences regarding project outcomes.

Fourth, we used the *R* (Core Team R, 2021) and *Julia* (Bezanson et al., 2017) programming languages and their corresponding network analysis ecosystems to implement analyses and visualize results. Finally, and in line with the SONA method, we presented and discussed findings of the survey with participants on a workshop in April 2023.

3.3. Measures and methods

In line with our three research questions, we used the following measures to (1) assess the appearance and magnitude of boundary-spanning learning in the *Innovation Space*, (2) to assess the robustness of these boundary-spanning ties, and (3) to determine the consistency of these ties with the hypothesized drivers of tie formation.

Knowledge-sharing. To allow for comparability and consistency across studies, we adopted a frequently used and proven item to qualify effective learning and knowledge adoption by asking (Glückler, 2014; Glückler & Hammer, 2017; Panitz & Glückler, 2020): "*who has helped you solve work-related problems or build new knowledge in the project*". Respondents chose individuals from a complete member list ($N = 150$) provided in the survey whose knowledge input they acknowledged as helpful. The dummy variable is 0 for contacts without receipt of input and 1 for those contacts who provided helpful input.

Boundary-spanning ties. We adapted the typology introduced in Section 3.2 to the context of the *Innovation Space*: type-1 ties represent all intra-organizational ties of acknowledged knowledge-sharing. When colleagues from one organization are assigned to different projects, these ties are still treated as intra-organizational and coded as type-1b ties. Type-2 ties represent inter-organizational knowledge-sharing among members working on the same project. Finally, type-3 ties include all instances of knowledge-sharing between individuals from different organizations and across different projects. We further distinguish *technical* knowledge sharing (type-3a) between people across organizations and projects from *non-technical* knowledge sharing (type-3b), including members of the PMO or the project of accompanying social science research. Note that due to the possibility of multiple project affiliations, technically there can be some overlap between the three sets of ties. Fig. 2 visualizes the three different networks of type-1, type-2, and type-3 relations and gives their respective edge counts and densities.

The dependent variable is the existence or absence of a type-3 boundary-spanning tie. Because the dependent variable is specified at the dyad level, independent and control variables are functions of the attributes of the actors involved in the dyad or the local network context of the dyad. Apart from determining the appearance and magnitude of boundary-spanning ties, we assess measures of three hypothesized drivers of their emergence:

Permanent geographical proximity. Two individuals who work in the same region are considered to be co-located. To assess co-location, all members were geocoded according to their workplace. The workplaces were geocoded according to the NUTS-3 regions in Germany. Hence, individuals in a dyad are defined to be co-located when the sites at which they are employed share the same NUTS-3 code, measured as a dummy variable.

Temporary geographical proximity. The *Innovation Space* hosted four different types of events: an annual members' meeting ($n = 4$), a regular forum including public audiences ($n = 6$), workshops among members ($n = 8$), and so-called insight sessions with presentations from the accompanying social science research project ($n = 14$). The score of each pair of individuals on temporary proximity equals the number of events which they had jointly co-attended, according to the survey responses. This score varies from 0 (= no co-attendance) to 27 jointly attended events for each dyad of individuals in the network. Since declining returns can be assumed for a high number of joint participations, the number of joint participations is logarithmized.

Networked reputation. In the survey questionnaire, respondents were asked whether they had established new learning contacts upon personal referrals forwarded by members in a governance function, i.e. members of the PMO or project managers of a technical project. Networked reputation, hence, is first measured as a binary variable, taking a value of 1 if an individual in a dyad reported having been referred to new contacts by a person holding a governance role (otherwise zero). We furthermore introduce a second, relational measure of networked reputation in the form of the geometrically weighted count of edgewise shared partners (GWESP), a robust standard statistic in network statistics. This measure captures transitive closure by modeling the tendency for two actors to form a tie when they share common partners, while

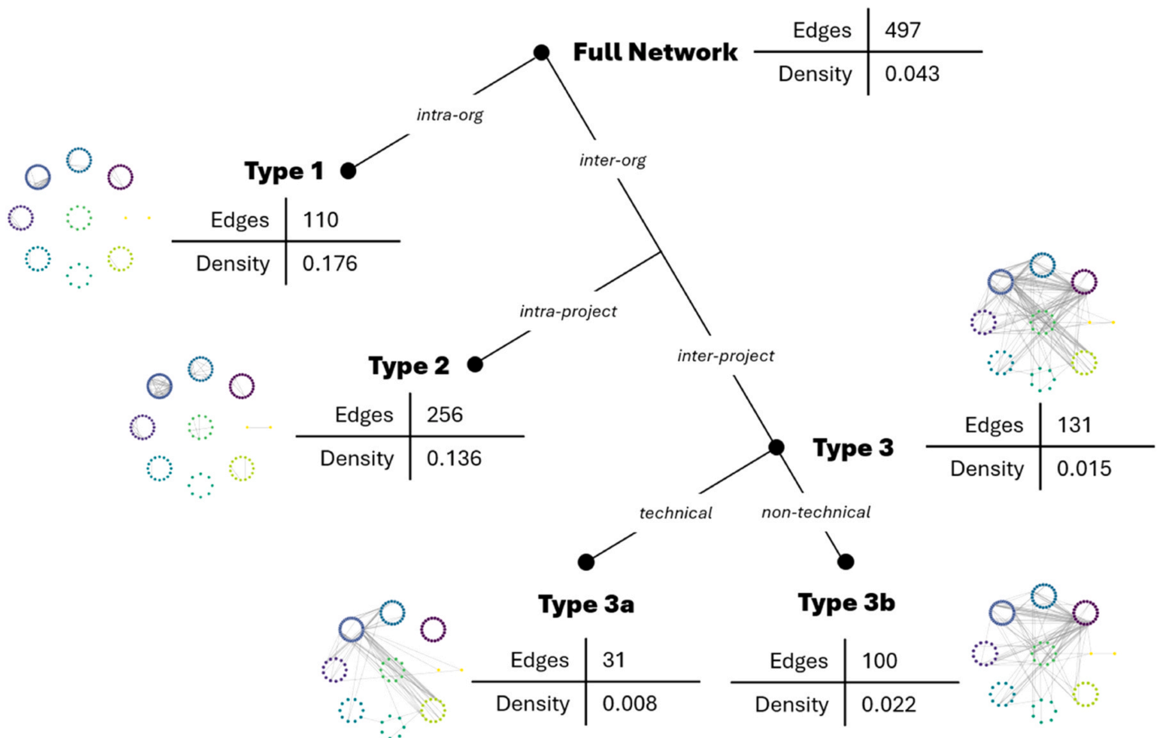

Fig. 2. Network statistics by type of boundary-spanning ties (edges) in the Innovation Space. Individuals in the network graphs are sorted to circles according to common project affiliation.

weighing additional shared partners geometrically to reflect diminishing marginal effects. While this is not specific to PMO referrals, it aims to capture the tendency to which contacts are established to your contacts' contacts, which is structurally consistent with a mechanism of referral.

Relational stability. Finally, we include reciprocity as a measure of relational stability because a relationship that is acknowledged by two actors can be expected to be a more capacious and stable channel for communication than an asymmetrical tie. Reciprocity is measured by a dummy variable which is 1 when for a tie $s \rightarrow r$ the reciprocal tie $r \rightarrow s$ also exists and 0 otherwise.

Based on these measures, we display simple descriptive statistics to investigate the distribution of knowledge sharing across the three conceptual types, with a focus on the occurrence of type-3 relationships (research question 1). To examine the network's sensitivity to membership turnover as specified in research question 2, we run a robustness simulation based on the knowledge network and the typology of boundary-spanning ties: After initially sorting all participants according to their individual degree (number of contacts), we record overall structural metrics while iteratively removing the most central actor step-by-step from the network.

Finally, we employ a statistical network model to model to test for consistency of the appearance of type-3 relations with the three conjectured conditions of permanent and temporary geographical proximity, and networked reputation (research question 3). We model the presence or absence of a tie for all pairs of actors in the network based on attributes of the sender, the receiver, or the dyad. Because relational data violate the usual assumptions of statistical independence, network models aim to account for different patterns of dependence among dyads, such as reciprocity or transitive closure. We here use the Frailty Exponential Random Graph Model (FERGM) proposed by Box--Steffensmeier et al. (2018), which makes use of the flexible pseudo-likelihood specification of the classical ERGM, the inferential shortcomings of which it adjusts by including random sender and receiver effects. These random effects have the additional benefit of accounting for actors' unmeasured motivation, visibility, or access to opportunities for collaboration, all of which can influence their likelihood of engaging in knowledge-sharing ties. We first fit a model to the whole network before explicitly focusing on type-3 ties. For the latter, we exclude all dyads that do not conform with the type-3 conditions, i.e. all dyads involving members of the same organization, or members of the same project, as outlined above. Table 3 summarizes the variables of the models. Data preparation and visualization have been performed using the Julia programming language and its package ecosystem (Bezanson et al., 2017). Models were estimated using the Stan probabilistic programming language and its R interface (Carpenter et al., 2017).

Table 3
Operationalization and measurement of dyadic variables.

Variable	Operationalization	Valuation
Knowledge sharing	A person has helped me solve work-related problems or build new knowledge for the project (no/yes)	dummy
type-3 tie	Knowledge sharing between organizations and across projects (no/yes)	dummy
Geographical proximity		
Permanent proximity	Co-location of individuals in the same NUTS-3* territory (no/yes)	dummy
Temporary proximity	Number of incidents of co-attendance of individuals at the same events (frq.); logarithmized to account for declining return log (1 + frq.)	numeric
Networked reputation		
PMO Referral	Member of a type-3 tie who reported to have made contacts through a referral by a project manager or PMO member (no/yes)	dummy
Transitive closure	Geometrically weighted number of edgewise shared partners	numeric

Note: * Nomenclature of territorial units for statistics.

4. Results

4.1. The occurrence of type-3 ties

After three years of operation, members of the *Innovation Space* had established a cohesive knowledge network, consisting of 128 actors and 793 ties of knowledge sharing. The survey comprises 65 active members who identified another 63 non-respondent individuals. The network among respondents comprises 497 edges and is subject to the subsequent analysis. Only eight individuals were disconnected from the knowledge network (*isolates*). To assess the quality of these relations, we asked survey participants to indicate if they had received inspirational input from other colleagues in the *Innovation Space*. More than three quarters of all participants indicated that they were happy with the contacts within their own (87 %) and across other projects (84 %). Additionally, more than half of all members (57 %) reported that they received inspiration from their other project members, an observation that reconfirms the value found in innovation collaboration. Of the 497 ties among respondents, 110 (22 %) are type-1 (intra-organizational) and another 256 (52 %) are type-2 ties (inter-organizational) all within a project (Fig. 2). Finally, 131 ties (26 %) were type-3 ties, spanning the boundaries across organizations *and* projects. Of these, 100 (20 %) involved individuals in governance roles (type-3b, i.e. PMO members or project managers), whereas only 31 (6 %) ties included technical members. Of these 31 ties, 10 involved members of the social science accompanying research project, leaving only 21 ties exclusively between technical project members (type-3a).

While project managers are members of a technical project, their work involves project governance and administration in addition to technical work. As one project manager highlighted: "*you actually spend an incredible amount of time on coordination and management tasks. Perhaps that shouldn't have been so surprising, but it's true that I imagined it would be a bit different at the beginning and wanted to do more substantive work*" (i13). Excluding project managers indicates that knowledge sharing across different technical projects by members involved primarily in technical and research work is scarce: Only 10 out of 497 (2 %) relationships qualified as truly technical boundary-spanning ties among non-lead roles.

Although the primary function of project managers is coordination and administration of a project, they often were also technical experts and involved in the technical implementation of their project. A notable example of this is a follow-up project that emerged from the collaboration between two project managers overseeing separate projects within the *Innovation Space*. One of these projects, as described in Section 4.2, assessed the technical feasibility of producing textile applications such as sports shoes from algae. The other focused on bio-based high-performance coatings for textile finishing. A type-3a relation was identified between these two projects (managers), specifically, between the product development knowledge domain and the textile research domain (Fig. 3). Based on their knowledge exchange, the project managers jointly developed a new project proposal that focused on textile finishing technologies, particularly water- and oil-repellent treatments, which was subsequently approved for funding within the framework of the *Innovation Space*.

All the 31 type-3a ties not only spanned the boundaries of projects but also of different knowledge subdomains (Table 2). When categorized into the six technical knowledge domains (Fig. 3), only two of these relationships were between actors of the same research domain (i.e. product development). Individuals engaged in fundamental textile research had the most diverse set of boundary-spanning learning relations. They maintained 16 inter-domain relations and so tapped into three other knowledge domains. Focusing on type-3a relationships (only among technical members), individuals from the product development domain most frequently served as knowledge senders to other domains, almost equally involving academic and corporate members. Moreover, about half of all type-3a ties entailed knowledge sharing between academia and industry. The actors engaged in type-3a collaboration predominantly focused on outputs related to product development (78.95 %), technology (52.63 %), and application (47.37 %), while contributions to service-related outputs remained limited (10.53 %). With respect to knowledge outputs, these individuals put stronger emphasis on academic publications (57.89 %) than on generating intellectual property (31.58 %).

Altogether, and to respond to research question 1, the *Innovation Space* has been a context in which type-3 ties did emerge even though in moderate magnitude. Because of the originality of the approach and the lack of comparable research on these ties, it is hard to evaluate if the numbers are low and what number of type-3 ties could have been expected. It is important to acknowledge that the Innovation Space in the textile bioeconomy had only operated a few years, and that across-project learning, knowledge sharing innovation collaboration was not part of any workplan in the individual projects. In the next step, we explore the stability of these ties (research question 2).

4.2. The robustness of type-3 ties

Type-3 ties not only occurred rarely, but they also proved vulnerable to membership turnover. When the ten most central actors were

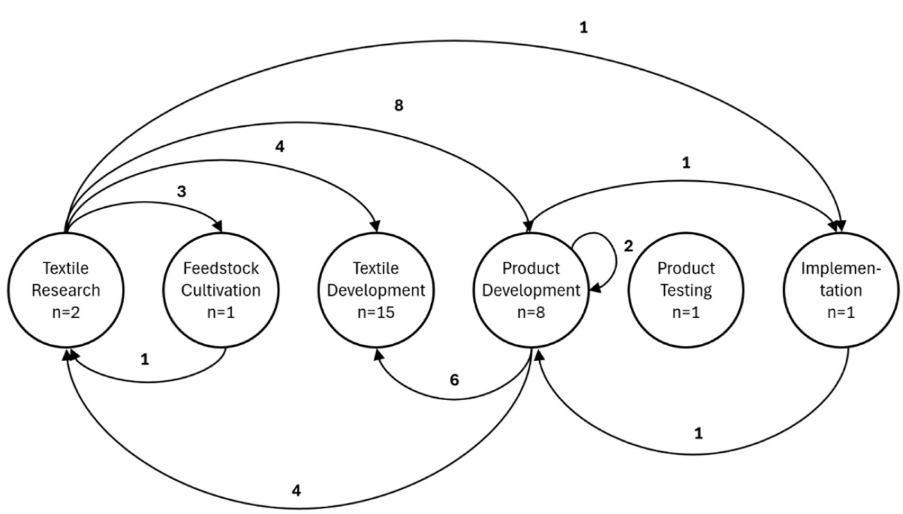

Fig. 3. Type-3a relations sorted by stages (n = number of assigned organizations) downstream the R&D value chain: The values of the edges indicate the number of type-3a relations.

removed in this fashion, more than half of the relations disappeared (Fig. 4a). However, despite this loss of knowledge sharing activity, the *mean pairwise reachability* does not fall below 85 %, indicating that the overall cohesion of the network remains intact (Fig. 4b). Even the removal of 20 or more actors does keep mean pairwise reachability up at 65 %. Yet, when distinguishing between the types of boundary-spanning ties, a different scenario becomes salient (Fig. 4c): With the removal of only 10 people, nearly all cross-project relations are lost, regardless of whether they are of type-3a or type-3b. Whereas governance relationships (type-4b) are naturally concentrated on a small set of individuals by design of the PMO, they are likely to be 'inheritable' in the face of personnel succession, because for formalized roles there are likely to be handover protocols. In contrast, because type-3a ties are not formally planned or even necessary for project completion, the channel for knowledge sharing they represent is more likely lost in the face of membership turnover. Simulating the removal of the most central actors represents a hypothetical worst-case disruption of the network. Interestingly, the structural vulnerability of type-3 ties is contrasted with a high degree of relational stability: Exponential Random Graph Models (Table 5, Section 5.3) show that especially type-3a ties exhibit a very high degree of reciprocity compared to the full network. The increased importance of mutual recognition indicates that existing type-3 ties might be more robust and carry higher capacity for knowledge sharing compared to otherwise more fleeting, asymmetric relationships.

Regarding research question two, we found that although type-3 boundary-spanning ties were found rare and structurally vulnerable to personnel turnover, they proved to be embedded into remarkably stable dyads: the majority of these ties were in fact reciprocal, reflecting knowledge sharing in both directions and highlighting the mutual benefits that boundary spanners enjoyed. Because membership turnover is a common phenomenon in organizations, both academia and industry, it turns out to be a real governance challenge for medium to long-term projects to build and preserve the knowledge embedded in boundary-spanning interpersonal ties.

4.3. The determinants of type-3 ties

To address the third research question posed in Section 3.2, we use Exponential Random Graph Modeling (ERGMs) to assess the statistical factors that are associated with the creation of a knowledge sharing tie. Table 4 provides descriptive statistics and pairwise correlations for the ERGM change statistics used in the models and the binary outcome variable y. There is generally no strong multicollinearity, with the strongest correlation (0.72) between 'same organization' and 'permanent proximity', which reflects the co-location of employees within the same organizational settings. This is further supported by the presence of a strong textile employment cluster in Aachen, where many employees of key organizations are concentrated.

Models 1 and 2 (Table 5) are baseline models for the full network with (2) and without (1) network effects. They reaffirm that there is a strong tendency towards sharing knowledge *within* projects and a certain bias towards sharing knowledge with members of the *same* organization. Given the *Innovation Space* architecture, this finding can be expected ex ante because it represents the regular communication to fulfill a collaborative project plan. Model 1 furthermore predicts an increased likelihood of exchange among co-located actors (permanent geographical proximity) and those who frequently attended the same events (temporary geographical proximity). Evidence for networked reputation is mixed: The actor-based measure of governance referrals has only a small and statistically uncertain effect. Including triadic closure

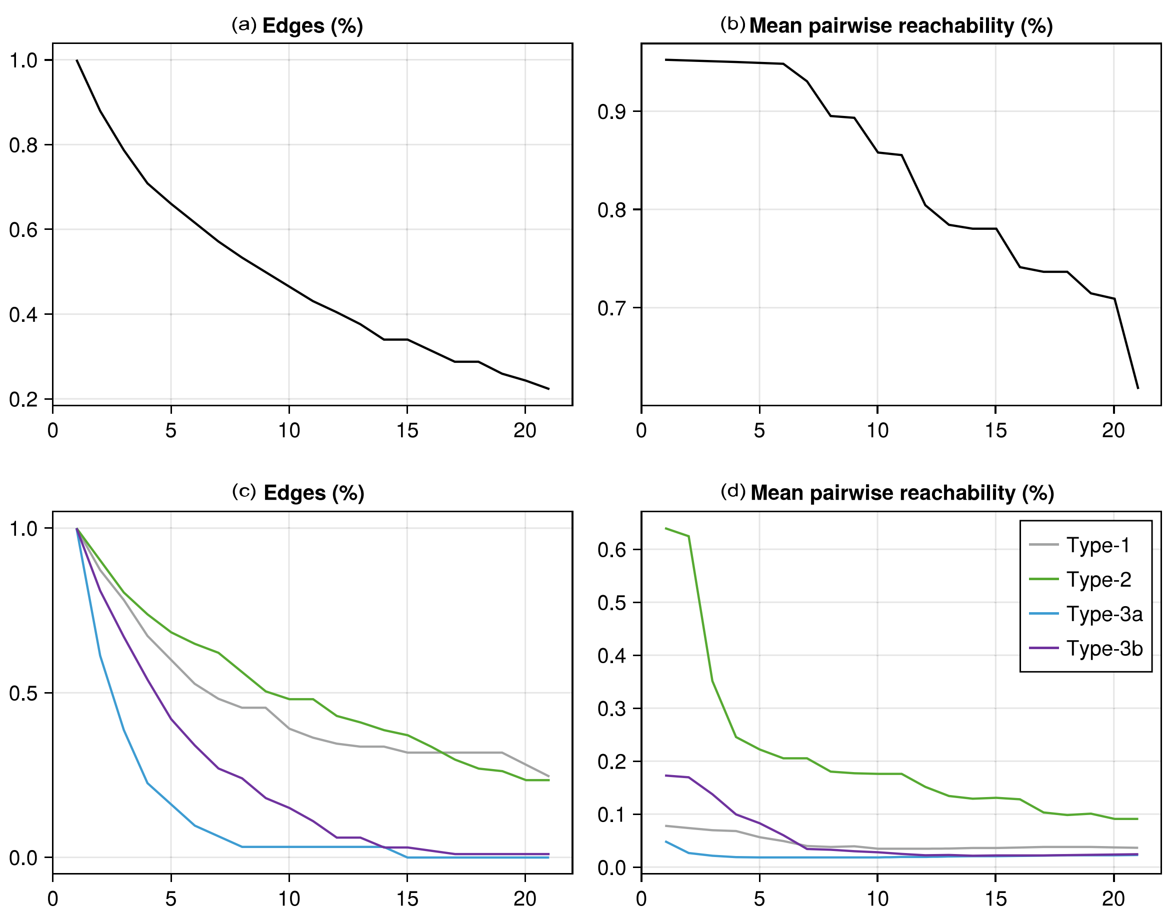

Fig. 4. Robustness simulation of the knowledge network. The x-axis represents the number of iteratively removed members, in order of degree centrality. The y-axis represents the share of all network members.

Table 4
FERGM summary statistics.

	Mean	SD	y	Same project	Same organization	Permanent proximity	Temporary proximity	PMO referral	Transitive closure	Reciprocity
y	0.13	0.34	1.00	0.41	0.22	0.17	0.13	-0.02	0.45	0.46
Same project	0.22	0.41		1.00	0.10	0.02	0.02	-0.03	0.36	0.41
Same organization	0.07	0.26			1.00	0.72	0.03	-0.02	0.23	0.22
Permanent proximity	0.13	0.34				1.00	0.11	-0.01	0.21	0.17
Temporary proximity	0.58	0.71					1.00	-0.04	0.21	0.13
PMO referral	0.43	0.50						1.00	-0.02	-0.02
Transitive closure	1.05	1.01							1.00	0.43
Reciprocity	0.13	0.34								1.00

Table 5
FERGM model results.

	M1 Full network	M2 Full network	M3 type-3	M4 type-3	M5 type-3a	M6 type-3b
Intercept	**-4.56 (0.30)**	**-5.47 (0.31)**	**-5.65 (0.50)**	**-6.31 (0.49)**	**-7.22 (1.06)**	**-6.34 (0.57)**
Formal structure						
Same project	**3.48 (0.18)**	**2.20 (0.18)**	-	-	-	-
Same organization	**0.99 (0.33)**	0.49 (0.35)	-	-	-	-
Geography						
Permanent proximity	0.55 (0.32)	0.43 (0.33)	**0.94 (0.42)**	0.78 (0.43)	-0.30 (1.07)	**0.98 (0.46)**
Temporary proximity	**0.66 (0.14)**	**0.41 (0.15)**	**1.28 (0.24)**	**0.77 (0.23)**	-0.38 (0.64)	**0.96 (0.25)**
Networked reputation						
PMO referral	0.13 (0.25)	0.05 (0.25)	-0.07 (0.39)	-0.08 (0.38)	-0.25 (0.69)	-0.03 (0.41)
Transitive closure	-	**0.81 (0.10)**	-	**0.76 (0.16)**	**1.16 (0.39)**	**0.65 (0.18)**
Relational stability						
Reciprocity	-	**2.01 (0.19)**	-	**2.79 (0.39)**	**4.37 (1.09)**	**2.22 (0.42)**
Sender SD	1.22	1.11	1.83	1.53	2.56	1.46
Receiver SD	1.13	1.00	1.36	1.20	0.94	1.21
ELPD (LOO)	-900.2 (34.8)	-794.5 (32.5)	-358.2 (26.4)	-325.7 (24.9)	-71.4 (11.8)	-249.4 (21.2)
n	3782	3782	2784	2784	1008	1776

Note: Coefficients are posterior medians, brackets indicate posterior standard deviations. Coefficients for which the 90 % credible interval does not contain 0 are in bold. ELPD gives the expectect log pointwise predictive density computed by approximate leave-one-out (LOO) cross-validation.

(measured by the geometrically weighted edgewise shared partners statistic), on the other hand, yields a large and highly significant effect. Including the network variable of reciprocity further increases the predictive accuracy of the model, as measured by its expected log pointwise predictive density. At the same time, it reduces the size of the aforementioned effects and increases their estimation uncertainty, with permanent proximity and organizational co-affiliation losing statistical significance.

Models 3 through 6 model the network of type-3 ties, with models 5 and 6 focusing on type-3a and type-3b ties, respectively. For the combined type-3 network, permanent and temporary geographical proximity are again statistically significant and strong predictors of the existence of a tie. While this finding persists for type-3b ties, it does not hold for type-3a ties, with the coefficients turning negative, and high statistical uncertainty making any judgement difficult. For networked reputation, a similar picture emerges as for the full network: Whereas the coefficient for PMO referral is not statistically significant in either case, transitive closure exhibits large and significantly positive effects. Although estimation uncertainty of the comparison makes a conclusive evaluation difficult, this effect is on average even larger for type-3a ties than for type-3b ties. This finding comes paired with an appreciably larger effect of reciprocity for type-3a ties than for the full or the type-3b network.

To summarize, the FERGM models show permanent and temporal geographical proximity to be consistent predictors in the emergence of knowledge sharing relationships, with the exception of technical boundary-spanning across projects (type-3a ties). The strong effect of temporary proximity for relationships involving governance actors (type-3b ties) indicates that project events represent an important stage on which members of the *Innovation Space* governance body can (re) connect to other members. While high estimation uncertainty also does not allow for the conclusion of no effect, the absence of the same effect for type-3a ties hints at real differences in the processes that spur or stifle knowledge sharing in some social, organizational, and geographic situations. For example, large and consistent effects of reciprocity and transitive closure suggest that interpersonal dyad- or group-specific processes that are not easily guided by aggregate policies and proximity effects are especially salient for serendipitous boundary-spanning exchange.

5. Conclusions

In this paper, we have proposed a relational typology of knowledge ties according to the extent of boundary-spanning that these ties achieve in a network of innovation collaboration. We have applied this typology in the context of a mixed-methods case study of an *Innovation Space*, i.e. a new support policy in Germany, which was explicitly designed to induce collaboration and boundary-spanning knowledge and innovation across different projects in the bioeconomy field. Applying a SONA mixed-method network approach (Glückler et al., 2020) to a network of 62 individuals who were affiliated with 39 public and private organizations involved in the *Innovation Space*, we made the following empirical findings: first, albeit being rare in number, truly technical type-3 knowledge sharing ties did emerge in the *Innovation Space*. Whereas roughly a quarter of all knowledge sharing relations cut across the boundaries of individual projects, only two percent of all knowledge sharing occurred explicitly among technical researchers. Individuals from the academic domain were slightly more frequently involved in type-3a relations than those from the corporate domain, highlighting their active role in boundary-spanning. Notably, actors involved in both product development and academic publication were particularly engaged in these relations. Furthermore, individuals from textile research, upstream the bioeconomy value chain, and product development, midstream of the value chain, were found to be active knowledge intermediaries who operated across domain boundaries. Second, regarding the robustness of type-3 ties, we found mixed evidence. Because technical type-3 ties were so scarce, they were structurally vulnerable to membership turnover, yet at the same time, they were relationally robust to the extent that they scored high on reciprocity and transitive closure. Those individuals involved in type-3 ties, acknowledged the value for their learning at both ends of the relationship. Third, whereas the hypothesized geographic and network conditions (proximity and networked reputation) were consistent with the full network of knowledge sharing, they were found inconsistent with the appearance of technical type-3 relations.

Governance measures such as organizing proximity through events and connecting individuals from different projects through PMO referrals had not yet produced significant effect on the emergence of technical type-3a relations within the Innovation Space. While the organization of events was generally beneficial for most types of knowledge sharing in our models, this cannot be concluded for type-3a relations. This finding is partly an effect of small sample size, and it may be due to the circumstance that (especially technical) knowledge cross-fertilization beyond projects rarely takes place during such events. In contrast, transitive closure and reciprocity proved to be significant predictors across all models. This suggests that while informal and network-based referrals were generally effective in fostering knowledge cross-fertilization, it may be challenging for a central governance entity such as the PMO to identify and initiate the most effective connections.

The study presented here has some limitations: First, its small-sample, cross-sectional design is not sufficient to demonstrate a causal link between the contextual factors and the emergence of ties. Longitudinal studies of the emergence and maintenance of knowledge ties in multi-project innovation collaboration could provide more conclusive evidence in this regard. Second, it is yet unclear which of the structural elements of boundary-spanning are idiosyncratic consequences of the way this specific *Innovation Space* was governed, as opposed to those features that are more general consequences of multi-stakeholder innovation collaboration. In the future, comparative study designs will help to shed light on the efficacy of structural mechanisms and governance instruments across different contexts.

Apart from these limitations, this study has useful implications for the growing literature on policy-induced collaboration. Methodologically, the introduction of the generic relational typology of boundary-spanning ties (type-1, type-2, type-3) helps researchers, policymakers and consultants to evaluate the extent to which policies intended to build and support collaborative innovation beyond the confines of organizations, projects, locations, and distinct knowledge domains, have been effective. We therefore offer a generic method to make empirical assessments of the magnitude and robustness of boundary-spanning network relations.

Given the heterogeneity and historical fragmentation of the diverse domains to be included in the bioeconomy, we had no pre-specified expectations regarding the magnitude of type-3a relations. Notably, actors operating in pre-competitive areas upstream the textile value chain were more likely to engage in boundary-spanning knowledge sharing than individuals involved in value stages further down the chain. This can be interpreted as an indication of competing motivations, such as the pursuit of scientific publication versus the protection of knowledge, and the resulting uncertainty. Moreover, the case study highlights that the bioeconomy is not yet a fully developed economic sector, but rather an emerging field held together by and depending on public funding.

Empirically, our findings suggest that the policy design of the Innovation Space can effectively facilitate unplanned knowledge synergies beyond the narrow scope of individual projects, knowledge domains and between science and industry by creating a space for mutual visibility and exchange, and only broadly bounded by the confines of an emergent technology field. In addition, by delegating authority to the self-governance of the *Innovation Space*, stakeholders are entitled to establish rules and procedures for developing and approving new projects on their own. In addition to the design of an opportunity space, proactive governance that promotes mutual awareness and exchange as well as personal encounters or even boundary-spanning collaboration, may further reinforce the emergence of type-3 knowledge sharing and subsequent innovation synergies. However, due to the relative salience of network mechanisms over geographical proximity, we learn that forging these synergy ties among technical staff continues to be a challenge, not least because researchers must comply with fixed tasks and schedules in the execution of their work packages and their pursuit of project goals. Hence, the innovation of an open funding format designed for synergy is not sufficient by itself, but pro-active and well-conceived governance of the network is crucially important to help innovation collaboration evolve more effectively to reap the benefits of boundary spanning synergies.

CRediT authorship contribution statement

Daniel Wagner: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization, Investigation. **Jakob Hoffmann:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization, Validation. **Johannes Glückler:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization, Project administration, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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