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Evaluating innovation networks in emerging technologies

Tessa van der Valk [a], Maryse M.H. Chappin [b,*], Govert W. Gijsbers [a]

[a] TNO, Brassersplein 2, 2612 CT Delft, The Netherlands
[b] Tilburg University, P.O. Box 90153, 5000 LE Tilburg, The Netherlands

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ABSTRACT

Interorganisational innovation networks are increasingly important for innovation in emerging technology fields. The performance of such networks can have a large impact on the future development of emerging technologies. A useful framework for the evaluation of innovation networks however does not yet exist. In this paper, such a framework is developed, using elements of the social network analysis literature and the resource-based view. This framework is subsequently applied to compare two policy-driven innovation networks: 1) the Center for Translational Molecular Medicine; and 2) the BioMedical Materials program. Based on this first empirical exploration of the framework implications for management and further policy development are formulated.

1. Introduction

An important characteristic of innovation in emerging technological fields is that it does not occur in isolation. On the contrary, innovations are generated and implemented by networks of interacting organisations and individuals. As a result, organisations increasingly organise their access to complementary knowledge networks [1]. Policy makers also emphasize the growing importance of collaboration networks for innovation. As indicated in a recent Policy Brief of the OECD 'the potential for innovation depends on how well knowledge circulates and how well the system is connected: policies to foster or enable the development of world class clusters and networks are thus of growing importance' [2]. A similar argument was used in a recent report of the Dutch Scientific Council for Government Policy [3]. It is thus indicated that the structure of a network has an influence on its performance in terms of innovation.

This increasing attention for the role of networks in innovation in emerging technological fields has given rise to specific policies aimed at stimulating network development in these fields. An example of this is the funding of public–private partnerships within so-called technological top institutes in the Netherlands. Such networks are neither true serendipitous networks, nor true goal directed networks [4]: they are compiled by individual projects and as such emerge bottom up but it is, at least to some extent, possible for policy makers to influence the further development of these networks, for instance by adjusting the boundary conditions of participation. To evaluate these policies, a framework to assess the performance of these networks is needed. Such a framework should also give insight into aspects that influence the overall network performance. In the academic literature on innovation, so far, research on collaboration networks for innovation have only limitedly addressed the issue of network performance (see also [5]): they have focused on the level of the individual organisation that is active in a network and not on the network as a whole [6–8]. In other words, studies on innovation networks have mostly addressed effects of network participation on the performance of an individual organisation and have not thoroughly dealt with the aspect of 'network innovative performance' [9]. For policy makers, it is however especially interesting to gain insights into the performance of a

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* Corresponding author. Tel.: +31 13 466 2523.
E-mail address: m.m.h.chappin@uvt.nl (M.M.H. Chappin).

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network as a whole. More specifically, they require insights into the possible determinants of network performance in order to evaluate the effectiveness of their policies.

We here aim to develop a framework for assessing and explaining innovative performance of a network. The central research question is: *what aspects can be identified that influence the innovative performance of a network and what implications for policy and management can be derived?* In this paper, we conduct a literature review to compile a first draft of such a framework, and apply this framework to two cases of policy-driven networks: the network of the Center for Translational Molecular Medicine (CTMM) and the network of the BioMedical Materials program (BMM). All projects that are part of these networks receive government funding and jointly they compile so-called 'technological top institutes' in their respective emerging technological fields of translational molecular medicine and biomedical materials. These case studies serve as first empirical explorations of the framework. Both networks aim to strengthen the innovative performance of the Netherlands in their respective areas of interest.

This paper is structured as follows: in the next section, we delve deeper into the concepts that could be included in a framework for the evaluation of innovation networks. The section ends with the draft framework for the assessment of the innovative performance of networks. In Section 3, the methods used in the empirical part of this study are discussed. Section 4 provides an overview of the results obtained followed by the conclusion and discussion of the paper (Sections 5 and 6, respectively).

2. Towards a framework for the evaluation of innovation networks

It appears that studies on whole networks are scarce [9]. In their review on whole networks Provan et al. [9] show few studies actually measure network outcomes, such as network effectiveness for instance. The studies on whole networks are relatively often focused on health and human services [9]. Provan and Milward [10] were the first to study network effectiveness in their study on the well-being of mentally ill clients. The goals of such networks are not focused on innovation and innovative outcomes, and studies on innovative performance of networks are virtually absent in the literature. As mentioned in the introduction studies can be found that focus on the level of the individual organisation and that address effects of network participation on the performance of an individual organisation (e.g. [11,12]). To measure the innovative performance of individual organisations, patent-related outcome measures are very often used [13].

To identify concepts that may influence the innovative performance of networks, different strands of literature are relevant. First of all, literature in the area of social network analysis (SNA) gives insight into concepts of network structure that may influence for instance the extent of diffusion of knowledge through a network [14]. These concepts may also influence the innovative performance of a network, but no empirical evidence is available to substantiate this suggestion. In this paper we therefore build on the studies that relate aspects of network structure to knowledge diffusion, and try to assess their influence on the innovative performance of a network. Networks not only differ in terms of their structure, but also in terms of the actors that participate in a network and the resources they contribute to the network [15]. Building on the resource-based view of the firm superior performance is a function of the resources that an organisation holds, as well as of the way these resources are exploited [16]. This latter aspect is laid down in the business model of the organisation [17]. The composition of a network in terms of the actors' resources and business models gives an indication of the extent of complementarity within a network. This complementarity or strategic fit likely benefits innovative performance [18]. To summarize, both the structure and the composition of a network thus need to be addressed here.

2.1. Aspects of network structure

The diffusion of knowledge through a network is reflected by its structure. According to Gay and Dousset [19], building on the work of Cowan and Jonard [14], this knowledge diffusion in its turn influences the innovative performance of an economy or sector. Furthermore, compared to random networks, networks that are structured enable significantly higher knowledge development rates in the future [20]. From social network studies, a variety of concepts is available. As indicated by Kilduff and Tsai [4] 'one of the beauties of a network approach to organizational studies is the extent to which the same network topics and measures apply at different levels' (p. 8). For this study, those concepts that concern the network as a whole are relevant, as this level of analysis is focused on. Both Kilduff and Tsai [4] and Wassermann and Faust [21] have provided overviews of network-level concepts. In their overview, Kilduff and Tsai [4] discern density, reachability or connectivity, centralisation and balance or clique formation. Wassermann and Faust [21], in their extensive overview of the field of social network analysis, include density and connectivity, structural balance and transitivity, cohesive subgroups and centrality. Although both sources use a somewhat different typology, the concepts referred to in both sources are similar. They both include the concept of cohesion (density and connectivity) and centralisation (or centrality or balance of the network). Furthermore, the concept of cohesive subgroups, also referred to as cliques, is also discerned in both. These three concepts of network structure were also found to be relevant in whole network studies [9]. Therefore, we focus in this paper on these three overall concepts for the examination of network structure: 1) cohesion; 2) cohesive subgroups; and 3) centralisation [4,9,21].

2.1.1. Cohesion

A first aspect that is thought to influence the performance of a network or cluster is the extent to which actors that are part of the network are related to one another, e.g. the cohesion of the network. In this respect, a limited number of relationships are thought to limit the performance of the network, which is also referred to as "weak network failure" [22]. Furthermore, cohesion enables the accumulation of social capital [23], which has been found in some studies to be beneficial for the innovative performance of individual actors within a network [24]. Cohesion may especially be important in applied research [25]. On the other hand, 'overembeddedness' also poses a threat to the performance of network participants: there is a threshold after which a higher embeddedness reduces the performance of individual participants in a network [26]. This overembeddedness reduces the extent to which the network is 'susceptible to newness' [8,22]. High cohesion reduces the variety of knowledge and therefore also the number of opportunities for novel combinations [27]. In other words, it causes redundancy [28]. Furthermore, high cohesion makes individual actors vulnerable in the event of an exogenous change as they do not have the knowledge to cope with this [26]. Based on prior literature it can thus be concluded that the relationship between network cohesion and performance is non-linear: performance is highest at moderate levels of cohesion. Both low and high levels of cohesion can be weaknesses in generating higher network performance.

2.1.2. Presence of cohesive subgroups

To examine the influence of network structure on the overall knowledge diffusion performance of the network, prior research has shown that networks that are highly 'cliquish', i.e. are composed of many cohesive subgroups, do not have an optimal performance in terms of knowledge diffusion [14]. This also goes for random networks, e.g. networks that have no cohesive subgroups at all [14]. The most efficient network architecture seems to be the small world topology, in which cohesive subgroups are connected to each other [14]. This type of structure on the one hand enables intensive knowledge sharing and the emergence of trust on the local level of a subgroup, but on the other hand also enables diversity as these subgroups are interconnected and the average path length in the network is relatively short [4]. For knowledge to diffuse through the network efficiently cohesive subgroups need to be interconnected.

2.1.3. Centralisation

Centralisation of a network entails the emergence of so-called 'hubs', e.g. above averagely connected central nodes. Next to these hubs, peripheral structures emerge that are comprised of nodes with a lower degree of centrality. This increased differentiation of the degrees of the nodes in networks can influence network performance in two ways. First of all, highly differentiated structures are generally more robust [29]; their structure is not likely to change due to the removal of a few nodes or edges from the network as scale invariance may occur [30]. Secondly, differentiation often implies centralisation: networks that have a small group of highly connected actors are often centralised around these actors and thus have a high centrality. Networks with a higher degree of centrality often operate more efficiently in case of problems and their participants have a clear sense of leadership roles in the network [31]. These advantages of more differentiated structures compared to random structures may also be favourable for innovation. As innovation takes time the robustness of the network is important. Furthermore, leadership has also been shown to be important for innovation [32]. Highly differentiated networks also pose an inherent risk: these networks depend heavily on their hubs. Strategic decision making of the organisations that are hubs in the network may significantly change the structure of the network as this decision making directly affects the composition of their ego networks [33]. Strategic decision making may also result in such organisations leaving the network, which would severely affect its structure. Summarizing, a more differentiated structure also poses potential strengths and weaknesses for a network.

To summarize, while studies have so far mostly focused on the implications of network structure and positions on the performance of individual participants in the network, several aspects can give rise to weaknesses or strengths of networks. These aspects include cohesion, the presence of cohesive subgroups and centralisation. In innovation studies, and more specifically in the studies of high technology sectors, aspects related to technology and technology dynamics cannot be omitted from the assessment of the potential performance of networks. In such sectors, technologies and networks have been found to co-evolve [12,34].

Analysing network structure only provides limited insight into the current state of an innovation network. Aspects with regard to the composition of a network and more specifically in regard to the resources available within a network are also relevant and are discussed in the next section.

2.2. Building on resource-based view: resources and business models

Within the resource-based view of the firm, resources are considered to be decisive in explaining performance differences between organisations [35]. Furthermore, the means by which these resources are exploited is also important [16]. In the context of innovation systems, Markard and Truffer [15] propose an actor oriented analysis that focuses on the resources and strategies of the actors in the system. The rationale for this is that actors, their resources and strategies to a large extent determine what activities will be carried out within the system or network. Furthermore, strategic fit and complementarity are needed to allow the emergence of synergies between organisations, eventually contributing to the performance of the respective organisations, and possibly the network as a whole. By combining complementary resources, networks of interacting organisations can be innovative [36]. The role of resources and strategies of actors that participate within a network is further elaborated in the following sections.

2.2.1. Resources of organisations participating in a network

Networks that are, at least to some extent, goal directed have a certain resource requirement [15]. In knowledge intensive sectors, the knowledge resources held by organisations are especially important. From the resource-based view of the firm it can be derived that, for a resource to lead to a sustained competitive advantage, this resource needs to be valuable, rare and not easily imitated or substituted [16]. Within a goal directed network, some knowledge resources may be especially valuable for attaining the goal that has been formulated. Furthermore, the rareness of such a valuable knowledge resource within the network may also be important to consider, as it influences the extent to which a resource requirement can be fulfilled. In other words, in regard to the knowledge resources held by network participants it is important to assess whether specific resources that are of importance to the network are missing, or have a relatively high risk of not being available in the future, due to dependence on only one or a few organisations. Partner scarcity, i.e. the lack of potential partners holding specific resources that are required for innovation, is then likely to hamper innovation [36]. On the other hand, when multiple network participants contribute similar knowledge resources to the network, this may lead to a reduced susceptibility to newness of the network [37], and eventually lock-in. This thus has to do with the coverage of knowledge fields by actors in the network and hence the rareness of important resources in the network.

2.2.2. Strategies of network participants: business models

Individual actors in a network, with their specific resources, can contribute the fulfilment of the network's resource requirement if their value generation strategy is in favour of 'unlocking' these resources to the network [15]. The value generation strategy of an organisation is laid down in its business model [17]. A business model describes in what way an organisation plans to commercialize its knowledge. Business models that are commonly distinguished in medical biotechnology are service or contract research organisations (CROs), tool or platform technology providers and product developers [38,39]. Furthermore, dedicated knowledge developers, such as research institutes, also play an important role in this field as it is science-based [40]. Generally speaking, the business models of individual actors that participate in a network should provide sufficient opportunities for complementarity, also referred to as 'organisational coherence' [41] and strategic fit [18]. It is difficult for firms that produce similar goods to find complementarities that justify collaboration [42].

2.3. Assessing the strengths and weaknesses of innovation networks

In the other sections of this chapter, several concepts relating to network structure and network composition have been identified that can be used in a framework to evaluate the strengths and weaknesses of networks in terms of its innovative performance. Table 1 provides an overview of the concepts discussed so far and the implication of their values in terms of strengths and weaknesses of networks with regard to innovation.

As is shown in this table, strengths and weaknesses can be identified for high and low measures on each of the concepts. In other words: the relationships between each of the concepts and the innovative performance of the network are proposed to be non-linear.

In the following section, the measures used to assess the different concepts relevant for network performance, structure and composition are explained. The method of data collection and description of the cases are also included.

3. Research methods

In this section, the methods for assessing the framework presented in Table 1 are discussed. The difficulty with this framework is that it is not yet known if there are certain optimal values for each of the indicators listed and what these values are. Therefore

Table 1
Framework for the evaluation of strengths and weaknesses of innovation networks.

Concepts	Weakness	Strength
Network structure		
Cohesion		
Lower	Weak knowledge flow	Network is more "open"
Higher	Chance of lock-in	Benefits to be expected from synergies
Cohesive subgroups		
Lower	Lack of strong local knowledge flows	Network is more "open"
Higher	Chance of local lock-in	Strong local knowledge flows
Centralisation		
Lower	Leadership unclear	Integration of the network is not heavily dependent on a few actors
Higher	High risk of network disintegration when leaders leave	Clear leadership
Network composition: resources and business models		
Coverage of knowledge areas		
Lower	Risk of lack of availability	High flexibility/less risk of lock-in
Higher	Risk of lock-in	Availability of knowledge is more secured
Variety of strategies (= combination of knowledge resources and business model)		
Lower	Lack of complementarities due to overlap	Easy to define common objectives
Higher	Lack of complementarities due to high variety	Perceived synergies facilitate collaboration

the potential strengths and weaknesses of networks can only be determined comparatively; i.e. by comparing the characteristics of a network over time, or by comparing different networks. We use the latter approach here, and make use of publicly available information on two different networks in emerging technological fields in the Netherlands. Additionally, to further explore and elaborate the effects of the different variables discerned on the innovative performance of the network, interviews were conducted with members of the management teams of both networks. In Section 3.1 the cases are described. In Sections 3.2, 3.3, and 3.4 the methods used to assess aspects of network structure, network composition, and the innovative performance of the network are explained, respectively.

3.1. Description of the cases

The cases studied here are of the Dutch Center for Translational Molecular Medicine (CTMM) and the Dutch BioMedical Materials program (BMM). The CTMM and the BMM program are government sponsored programs that aim to stimulate innovation through the support of public–private partnerships. Their activities were initiated in 2007 and 2008, respectively. The CTMM and BMM program each focus on their own respective focal areas. The CTMM “is dedicated to the development of medical technologies that enable the design of new and ‘personalized’ treatments for the main causes of mortality and diminished quality of life and the rapid translation of these treatments to the patient” [43]. Within the BMM program the focus lies on the development of new biomedical materials. Its activities therefore combine efforts in the fields of innovative materials and polymers, and healthcare. Within both programs, specific disease areas are defined that are considered to be ‘core areas’, such as cancer and cardiovascular diseases. In both cases, university hospitals are considered to provide the necessary input of clinical knowledge. In both programs large multinational firms are involved as well as smaller, start-up firms. All participants are obliged to provide matching for the financial support received by the government, either in the form of additional funds, or in hours spent on the projects. The objectives of both networks are similar: their primary aim is to stimulate innovation in their respective focal areas. The proposed benefits are two-fold: 1) health benefits for patients; and 2) benefits for the Dutch economy. Because of the highly similar background and contexts of the CTMM and BMM networks they are considered to be sufficiently comparable and therefore useful cases for use in a first explorative assessment of the framework.

3.2. Assessing elements of network structure

Data on collaboration projects that have been set up as part of the first calls of the CTMM and BMM are publicly available online. Using these data the networks can be compiled and the different aspects of the structure of a network can be examined. Wassermann and Faust [21] provide an extensive overview of possible measurements, both concerning the position of individual nodes in the network and the network as a whole. In view of the focus of this study, only measures relevant for the network as a whole are used. This is a relatively limited set of measures included in the extensive overview of Wassermann and Faust [21]. Measures addressing network cohesion are the density of the network, its average path length and diameter (longest possible path in the network). Together, these measures provide information on both the relative number of linkages in the network (density) and the extent to which these linkages effectively connect different nodes in the network (average path length and diameter). Subsequently, the presence of cohesive subgroups can be measured by calculating the clustering coefficient of the network. This coefficient reflects the average density of the clusters around individual nodes in the network. To draw any conclusions on the presence of cohesive subgroups the clustering coefficient of the network needs to be compared to the overall density of the network. If the clustering coefficient is significantly higher than the overall network density, cohesive subgroups are present [44]. Finally, network centralisation can be examined by calculating the overall network centralisation index, and skewness and kurtosis of the distribution of the degrees. The centralisation index provides an overall insight into the inequality of centrality of individual actors in the network [44], while the skewness and kurtosis can be used to further characterise this inequality by comparing the degree distribution to a normal distribution [45]. The skewness of the degree distribution provides information on whether there are many nodes with a relatively high degree (positive skewness) or many nodes with a low degree (negative skewness). The kurtosis reflects the ‘peakedness’ of the distribution. A positive kurtosis means that the distribution is peaked, i.e. it has some nodes with an extremely high degree. A negative kurtosis indicates a relatively flat distribution compared to the normal distribution. The measures that are relevant for the different concepts distinguished in the theory section are summarized in Table 2.

Some of these network measures are interrelated; for example: if the density is low, then the diameter is likely to be high and the other way around. Network centralisation measures the degree to which a network is centralised around a few relatively central nodes, which is related to the skewness and kurtosis of the degree distribution of the nodes in the network. Furthermore, networks with a high density generally have a low centralisation as all entities are highly connected.

To assess the different measures we make use of network analysis program UCINET [46]. Within UCINET the different measures can be calculated and the network data can also be visualized using NetDraw [47]. The original data that is available is a so-called two-mode network, i.e. a network consisting of two different types of entities, namely projects and participants. For conducting the calculations, the two-mode network needs to be transformed into a one-mode network, in which only participants are included. The linkages between participants indicate joint participation in a project. For the analysis, the values of the linkages, i.e. the number of projects in which two organisations collaborate, are not taken into consideration.

Table 2
Measurement of concepts of network structure.

Concept	Measure	Calculation	Range of value	Meaning of high value of measures
Cohesion	Density	The total number of present ties divided by the total number of possible ties	0 to 1	For density: the network is densely connected
	Path length: average	The average length of all paths between all nodes in the network	>0	For path length and diameter: the distances between the entities are long
	Path length: diameter	The size of the longest possible path between two nodes in the network	>0	
Presence of cohesive subgroups	Clustering coefficient	Mean weighted of the clustering coefficient of all actors	0 to 1	The network comprises of different clusters.
Centralisation	Degree distribution	Skewness and kurtosis of the distribution of degrees	No limited range	There are clear hubs among a large number of more limitedly connected others.
	Centralisation index	The degree of inequality or variance in the network as a percentage of that of a perfect star network of the same size [44]	0 to 100%	

3.3. Assessing elements of network composition

Data on the composition of the networks, i.e. on the knowledge resources and the business models of the individual organisations that take part in the network, are derived from the websites of these organisations. For identification of knowledge resources of firms active in emerging technological fields websites are considered to be a more relevant source of information than patent databases [48]. Aspects of business models, such as the positioning of a firm within the value chain are also publicly available on websites of organisations, as they use their site to inform potential customers and investors. Table 3 provides an overview of the different business models that are relevant for the cases under consideration, as well as their definition (see also [38,39]).

To assess the knowledge resources held by the actors that participate in the networks, typologies of knowledge fields that are relevant for both programs need to be developed. Within the CTMM, two technology platforms are addressed: 1) molecular diagnostics; and 2) molecular imaging. These platforms aim to contribute to the stratification of patients; and early diagnosis and determining of predispositions and hence evidence-based medicine [43]. Developments in the fields of molecular diagnostics and imaging build on a set of tools, including: 1) biomarkers (DNA/RNA or protein); 2) biosensors, including ligand development (such as DNA micro chips); 3) contrast agents; and 4) imaging systems and software.

Within the BMM program, several possible applications that can be developed are defined, namely 1) developing implants; 2) coatings; 3) drug delivery systems; 4) passive scaffolds and 5) active scaffolds [49]. Overviews of the knowledge fields that are important for the two programs are given in Table 4.

Also, organisations may provide input that does not concern the core focus of the networks. For universities and other knowledge institutes, the focus of the specific divisions that participate in project need to be known to allocate them to these different fields. As this information was not available, universities and multidisciplinary research institutes could only be subdivided into 'general' (for large multidisciplinary) and 'clinical' (for university medical centers).

On the level of the networks as a whole, the availability of knowledge and variety of combinations of business models and knowledge fields needs to be assessed. This can be done by allocating the organisations that are active in the networks to the different knowledge fields and business models. A matrix can then be compiled in which individual organisations can be depicted according to the combination of their knowledge resources and business model.

3.4. Assessing the innovative performance of a network

For the measurement of innovative performance one can distinguish between quantitative measures and qualitative measures. With regard to the former, patent data [13,50] and bibliometrics (academic papers and citations) are often used by scholars that focus on the level of the organisation. These measures can also be used here to gain a first insight into the innovative performance of the networks. However, both networks studied here are only just emerging, and patents and publications and especially citations may not have been achieved yet. Therefore, we complement these quantitative insights with qualitative insights on network performance of the managers of the networks. These insights were gathered in interviews with managers of both networks. The managers were asked

Table 3
Overview of possible business models.

Business model	Definition
Dedicated knowledge developer	Research institute that is aimed at further development of specific knowledge
Service or CRO (contract research organisation)	Provides services or contract research within a specific field, based on specific internal knowledge.
Platform or tool developer	Develops technology platforms or tools that are sold or licensed out B2B. The tools can subsequently be applied in product development
Product developer	Develops concrete products, which can either be diagnostics or biopharmaceuticals or other end products

Table 4
Knowledge fields that are relevant for the CTMM and BMM programs.

CTMM: molecular diagnostics and imaging
Biomarkers: characteristic that can be evaluated as an indicator of a biological process, such as DNA, RNA and proteins
Biosensors, including ligand development
Contrast agents
Imaging systems and software

BMM: biomedical materials
Implants: improvement of traditional materials
Coatings: functional (for instance anti-microbial) coatings for medical devices
Drug delivery systems: targeted delivery and controlled release
Passive scaffolds: for functional restoration of tissue
Active scaffolds: for tissue regeneration

to elaborate on the achievements of the network in regard to innovation, and indicate if these achievements so far meet the expectations. In the interviews, the managers were asked to reflect on the innovative performance of the respective network, and to elaborate on the role of different concepts of network structure and composition in attaining this performance. During each of the interviews a graph of the respective network was shown, but the interviewees were not informed about the specific findings on network structure and composition prior to or during the interviews. Furthermore, the respondents were asked to explain the governance of the networks, i.e. the way in which the network is managed. This enabled us to derive implications for management.

The results obtained using all measures described in the previous sections are discussed in Section 4.

4. Overview of the results obtained

In Figs. 1 and 2 the networks of the first call of CTMM and BMM programs are given, respectively.

From these figures it already becomes clear that projects within the CTMM network are larger (i.e. include more partners) than those within the BMM network. The CTMM network is larger: it consists of 63 organisations that collaborate in 9 projects, while the BMM network consists of 27 organisations active in 7 projects. In the BMM network, a larger share of the participants participates in more than one project (about 56% compared to 37%). In the CTMM network, the most connected organisations are the MUMC (University Medical Center Maastricht), the UMCU (University Medical Center Utrecht) and Philips (electronics, medical technology and imaging company). In the BMM network the UMCU, MUMC, TUE (Eindhoven University of Technology) DSM and the

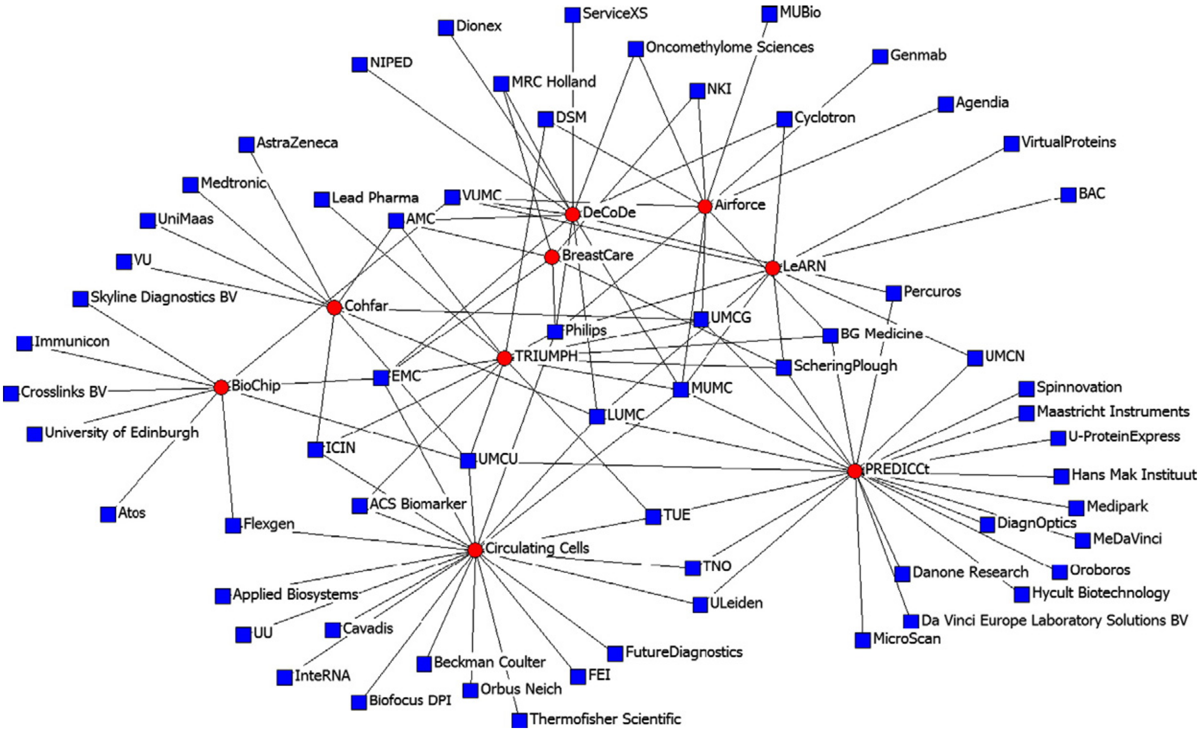

Fig. 1. Two-mode network of the first call of CTMM (red circles are projects; blue squares are participants).

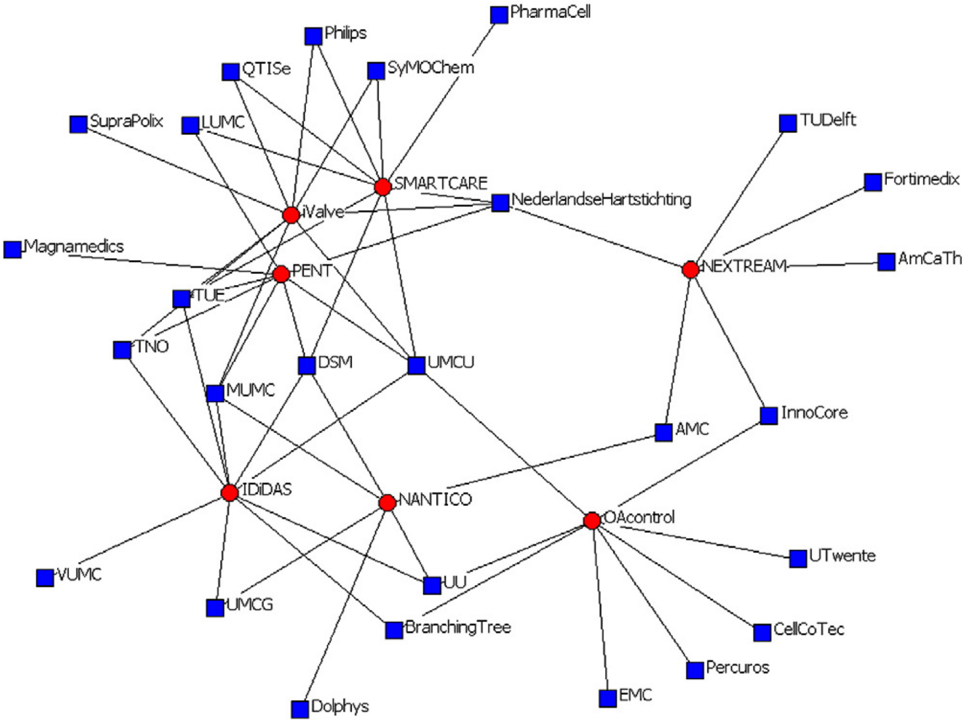

Fig. 2. Two-mode network of the first call of the BMM program (red circles are projects; blue squares are participants).

'Nederlandse Hartstichting' (Dutch foundation for cardiovascular diseases) are most connected. University medical centers thus play an important role in both networks.

4.1. Results on network structure

Table 5 lists the structural characteristics of both networks. The density of the BMM network is higher as a larger share of participants is active in two or more projects. The clustering coefficient of both networks is close to 1 (0.861 and 0.816 for CTMM and BMM, respectively) and much larger than the overall density of both networks (0.3497 and 0.4074, respectively). The reason

Table 5
Characteristics of the two networks.

	CTMM		BMM	
	2-mode	1-mode	2-mode	1-mode
Descriptives				
No. of organisations	63	63	27	27
No. of relationships	114	683	55	143
No. of organisations with more than 1 project	23 (0.365)		15 (0.556)	
No. of projects	9		7	
Cohesion		0.3497 (SD = 4769)		0.4074 (SD = 0.4914)
Density				
Average path length [a]	–	1.650	–	1.736
Diameter	–	2	–	3
Presence of cohesive subgroups	–	0.861	–	0.816
Clustering coefficient				
Centralisation				
Centralisation index	–	52.17%	–	43.23%
Degree distribution				
Skewness		0.8795		0.5963
Kurtosis		0.3969		−0.5388

[a] The average distance, diameter, clustering coefficient and degree distribution could only be calculated after transforming the two-mode network containing both projects and organisations to a one-mode network containing only organisations that are linked because of joint project participations.

Fig. 3. Business models of CTMM participants.

for these high values seems to be that the networks are comprised of a limited number of projects in which multiple partners collaborate, and these projects are then the clusters that comprise the network.

The values for skewness and kurtosis of the degree distributions of both networks are nearly admissible deviations from zero [45], which indicates that a normal distribution of degrees of the nodes in the networks can be assumed. Looking at the overall network centralisation index, it can be seen that the CTMM network is relatively inequal compared to the BMM network. The inequality of the CTMM network is 52.17% of the maximum possible inequality, while the inequality of the BMM network is 43.23% of the maximum possible inequality.

To summarize, in regard to structure the BMM network is smaller and more densely connected. A reason for this is that the share of organisations that participate in multiple projects is quite high. The CTMM network on the other hand is much larger in terms of the number of participants, and less densely connected. The inequality in the CTMM network, in terms of degrees of the organisations active in the CTMM network, is larger than in the BMM network. Both networks have a relative high clustering coefficient.

4.2. Results on network composition: resources and business models

In this section, the results in regard to the resources held by network participants and their strategies for resource exploitation are presented. In the following section the CTMM case is discussed, followed by a discussion of the BMM case in Section 4.2.2.

4.2.1. Specific results on the CTMM case

In Fig. 3, the business models of the organisations that participate in the CTMM network are given. Relatively many of the organisations are knowledge institutes. Of the firms that participate in CTMM most are product developers. Next to these, there are an almost equal number of B2B suppliers of tools and CROs.[1]

The frequency distribution of the knowledge fields on which these firms focus is given in Fig. 4. In this figure, knowledge institutes are listed separately, subdivided into those possessing clinical knowledge and those of a more general nature. As is shown in this figure, many firms active in the CTMM network develop diagnostic products, thereby combining two of the core knowledge areas of the CTMM, biomarkers and biosensors. In addition, several firms are engaged in the production, purification and analysis of DNA, RNA or proteins, and several others in pharmaceuticals.

One last participant is specifically focused on developing contrast agents, and a few others have knowledge of diverse fields. As can be seen in the cross table below, two of these firms are CROs, two others develop products and one is a B2B supplier of tools.

As shown in Table 6 product developers that are active in the CTMM network are mostly developing diagnostic products. But several are also active in the fields of pharmaceuticals and in electronics and medical devices. B2B suppliers of tools and CROs generally offer a wide range of services and tools, for multiple applications or application areas. Overall, the CTMM network includes relatively many firms active in the fields of diagnostics, imaging, and DNA/RNA/protein production and analysis. The number of developers of diagnostic products is especially high.

4.2.2. Specific results on the BMM case

Within the BMM network, only knowledge institutes, product developers and CROs are active. The majority of participants are knowledge institutes, nine are product developer and four are CROs (see Fig. 5).[2] There are no firms in this network that specialise in supplying tools to other firms.

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[1] Three participants were not included in this analysis because they only indirectly contribute to the project as they are not technology-oriented (two business consultancies, one office of a science park).

[2] One participant, a venture capital firm, was not included in this analysis because this firm only indirectly contributes to the program.

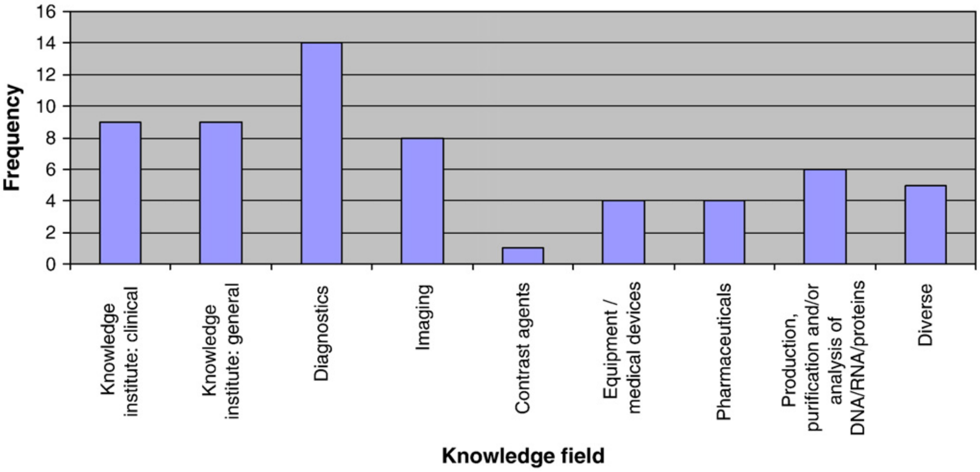

Fig. 4. Knowledge fields CTMM participants.

The firms active in the BMM network are relatively specialised. As can be seen in Fig. 6, most firms that participate in the BMM network focus on areas that belong to the core activities of the BMM program (drug delivery, active scaffolds, polymers and implants). For each of these applications, only a limited number of firms are present, ranging from four in the field of drug delivery to only one on the field of implants.

In addition, one is a diagnostics firm and one is focused on medical technology and imaging. Three firms have knowledge that is specifically focused on the development of polymers. Polymers are of general use to the program as they can be used in all kinds of medical devices.

In Table 7 the participants in the BMM network are subdivided according to their knowledge resources and business models. As can be seen in this table, the individual organisations are relatively scattered across this table, and there is no single strategy that relatively many BMM participants adhere to. There is thus, compared to the CTMM network, a relatively large variety in the strategies of BMM participants.

4.3. Results on the innovative performance of the networks

Based on the interviews it can be concluded that both networks are at this moment starting to generate innovative performance. In regard to quantitative measures, it can be noted that the CTMM network has now filed the first three patent applications. Patent applications will be filed by members of the BMM network in the near future, as the first inventions are now being developed. Also, in both cases the first articles have been written. Due to the proposed duration of the projects none of them has been completed yet, but according to the managers of both networks the projects are proceeding as planned. In both networks, some small delays have been incurred because of the financial crisis and lack of sufficiently qualified personnel. These issues have mostly been resolved now and progress can be made. Overall, the managers are satisfied and positive about the innovative performance of the networks and so far the innovative outcomes meet their expectations. Section 4.4 continues with a summary of the results and a further reflection on these results using the insights obtained during the interviews.

Table 6
Characterisation of strategies of CTMM participants.

	Knowledge institute	B2B supplier of tools	Product developer	CRO	Total
Knowledge institute: clinical	9	–	–	–	9
Knowledge institute: general	9	–	–	–	9
CTMM core areas					
Diagnostics (biomarkers and biosensors)	1[a]	3	9	1	14
Contrast agents	–	1	0	0	1
Imaging systems and software	–	3	1	4	8
Other knowledge areas					
Equipment/medical devices	–	1	2	1	4
Pharmaceuticals	–	0	4	0	4
Production, purification and/or analysis of DNA/RNA/proteins	–	2	0	4	6
Diverse	–	1	2	2	5
	19	11	18	12	60

[a] One research institute specialised in diagnostics was included. This was an exception: in general, knowledge institutes could only be subdivided into ‘general’ and ‘clinical’.

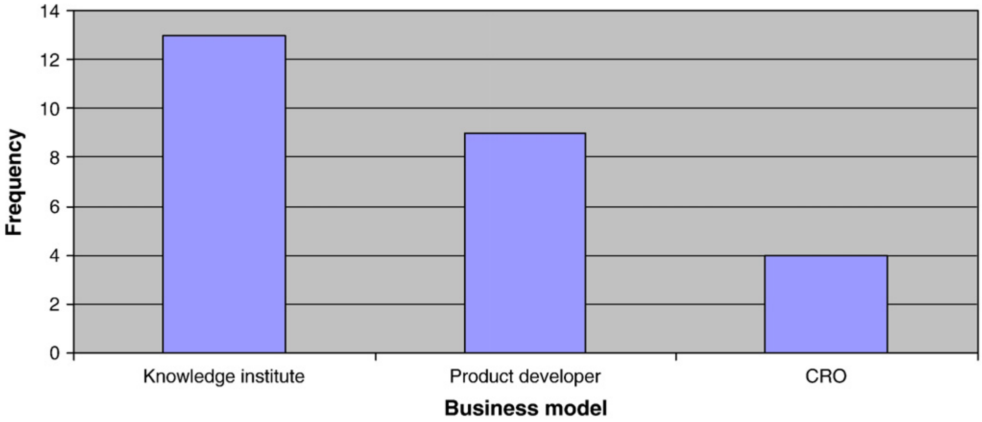

Fig. 5. Business models of BMM participants.

4.4. Assessment of strengths and weaknesses

During the interviews managers of both networks reflected on the concepts specified in this study, and their influence on innovation. Based on these interviews, an assessment of the strengths and weaknesses of both networks in regard to innovation can be made.

Using the data presented in the previous sections, a first indicative overview of comparative strengths and weaknesses of both networks can be given. This overview is given in Table 8.

These findings can be summarized as follows: the cohesion of the BMM network is higher than that of the CTMM network. Therefore, the BMM network is more susceptible to lock-in than the CTMM network. On the other hand, it could also be that within the CTMM network potential synergies are insufficiently utilized. In the interviews it became clear that in the CTMM as well as in the BMM network they acknowledge the importance of learning from other projects. Cohesion is generally seen as a strength. The managers of both networks stimulate cohesion in several ways. For instance, they organise several meetings with all partners to discuss the overall progress of the network. Also, individual projects are analysed by the management and lessons learned are distributed among the organisations in the network. The BMM network now has its own educational program and stimulates interaction and collaboration between parties that otherwise would not collaborate.

Looking at the existence of cohesive subgroups in both networks, it can be stated that both networks are dominated by project structures and that this may result in a lack of non-local ties and thus local lock-in. But it is also a possible strength with regard to knowledge flows. This is also what came up during the interviews. The interviewees stressed the importance of within project communication and collaboration for the innovative performance. Trust is seen as very important. As trust requires strong local collaboration, it became clear that cohesive subgroups are important for the innovative performance of the networks.

The CTMM network is a bit more centralised, indicating that compared to the BMM network within the CTMM network there are a few relatively central organisations. An advantage of such a configuration is that it provides the network with some extent of direction, as there are central organisations that can act as leaders. On the other hand, there is a higher risk of disintegration when these leaders decide to leave the network. Within the BMM network, centralisation is lower, which could possibly lead to unclear or potential lack of leadership. It is for now unknown to what extent either configuration limits or enhances the performance of the networks. The

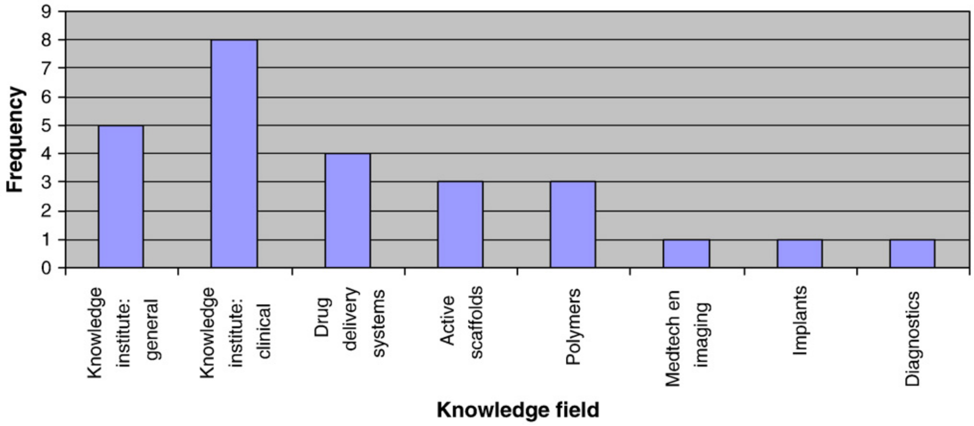

Fig. 6. Knowledge fields of BMM participants.

Table 7
Characterisation of strategies of BMM participants.

	Knowledge institute	Product developer	CRO	Total
Knowledge institutes				
General	5	–	–	5
Clinical	8	–	–	8
BMM core areas				
Implants	–	1	0	1
Drug delivery systems	–	3	1	4
Active scaffolds	–	2	1	3
Polymers (for coatings, scaffolds and devices)	–	1	2	3
Other knowledge areas				
Diagnostics	–	1	0	1
Medtech and imaging	–	1	0	1
	13	9	4	

management of both networks acknowledges the fact that some organisations are more connected than others. The BMM management explained that you need at least some very active organisations. As indicated by the respective manager: “There should be a core of organisations, ideally a combination of private firms and universities, that take up central positions in the network, and thereby show that they regard the network as important”. Furthermore, such a core of organisations is thought to contribute to achieving sufficient focus within the network and its future sustainability. On the other hand, it was also indicated that such a core should not be too dominant; it should be complemented with a strong overall network in terms of density.

Delving deeper into differences in regard to network composition of the two networks, it can be concluded that the extent of coverage of knowledge is more extensive within the CTMM network and therefore its availability in the future is more certain. In the BMM network, several quite crucial knowledge resources (for instance scaffolds, implants and imaging) are only held by a few of firms that participate. From the interviews it became clear that it sometimes is very difficult to find the right partner with the specific knowledge. As indicated by the manager of the CTMM network “Partners are sought based on the specific knowledge they have, but in principle they need to be Dutch. Only when there really is no appropriate candidate in the Netherlands would we search abroad”.

In regard to the variety of strategies, it needs to be mentioned that the CTMM network has a relatively high share of participants that are diagnostic product development firms. While this field is a core field in the activities of the CTMM it may lead to difficulties in finding a balance between cooperation and competition. In both networks a large overlap in terms of knowledge fields and business models is not preferred. Within the projects of both networks, no overlap of strategies is preferred. Complementarity of strategies is considered to be crucial for innovation. As specifically indicated by the BMM manager: “Complementarity is preferred so that one is able to value the input of others and one is able to understand one another”.

To summarize, in the framework for assessment of innovative performance of a network presented earlier in Table 1, each concept was indicated to possibly have a non-linear influence on the innovative performance of the network. Based on the reflection of the managers of both networks on these concepts, it can now be indicated that: 1) high cohesion is primarily perceived to be beneficial for the innovative performance of the network; 2) centralisation of the network is also perceived to be beneficial, but only up to a certain extent. Very high centralisation decreases overall cohesion in the network; 3) limited coverage of certain important knowledge fields has been indicated as a weakness; and 4) high variety of strategies is primarily perceived as a strength. Overlap is considered not preferred.

Table 8
Framework for the evaluation of strengths and weaknesses of networks.

Concepts:	Weakness	Strength
Network structure		
Cohesion		
Lower	CTMM: weak knowledge flow, risk of disintegration	CTMM: network is more “open”
Higher	BMM: chance of lock-in	BMM: benefits to be expected from synergies
Cohesive subgroups		
Lower	–	–
Higher	CTMM and BMM: chance of local lock-in	CTMM and BMM: strong local knowledge flows
Centralisation:		
Lower	BMM: risk of leadership being unclear	Integration of the network is not heavily dependent on a few actors
Higher	CTMM: high risk of network disintegration when leaders leave	Relatively clear leadership
Network composition		
Coverage of knowledge areas		
Lower	BMM: risk of lack of availability (in the future)	BMM: high flexibility/less risk of lock-in
Higher	CTMM: lack of flexibility	CTMM: availability of knowledge is more secured
Variety of strategies		
Lower Higher	CTMM: this network includes relatively many firms that develop diagnostic products; may lead to difficulties in balancing collaboration and competition.	

5. Conclusions

Returning now to the central research question of this paper, which is *what aspects can be identified that influence the innovative performance of a network and what implications for policy and management can be derived?* Based on a literature study it can be concluded that the analysis of the structure as well as the composition of innovation networks can provide insight into strengths and weaknesses. Elements that can be informative for the assessment of the overall structure of a network are cohesion, the presence of cohesive subgroups and centralisation. In regard to network composition, the availability of knowledge resources and diversity of strategies was focused on. In this paper, this framework was applied to the cases of two public–private policy-driven networks in the Netherlands, namely the CTMM and the BMM network.

In general, both networks are considered to be performing well. Using the framework several potential strengths and weaknesses for the future development of both networks were identified. In the interviews, managers of both networks reflected on the concepts of network structure and composition used here and their relation to the innovative performance of the network. It can be concluded that compared to the BMM network, the CTMM network has two potentially important weaknesses: 1) the cohesion of the network is lower; and 2) relatively many diagnostic product developers participate so there is an overlapping of strategies, which may lead to difficulty in finding a balance between collaboration and competition. As for the BMM network, the most important potential weaknesses are: 1) a relative lack of centralisation and hence leadership; and 2) limited coverage of some knowledge fields leading to a risk of a lack of this knowledge in the future. An overview of the suggestions for management and policy are given below in Table 9.

In the case of the CTMM network, a search for promising additional synergies that may be present between organisations that are active in the network can be fruitful. Also, managers of both networks stated that they aim to increase the cohesion of the network as this is thought to favour innovation. On the long term, cohesive networks may hamper innovation, and new relationships with organisations that are new to the network may be needed [51]. Especially in case of scarce knowledge resources, it may be necessary to open up the networks to foreign partners. Especially in the case of the BMM network there seems to be a certain partner scarcity in some important knowledge areas. By focusing mostly on the Netherlands, both networks may induce ‘partner scarcity’. In the future, a more international orientation of the networks could contribute to their long term sustainability. This brings us to a suggestion for policy makers: in high technology fields where policy makers want to stimulate developments by stimulating network development, foreign participation should be considered. Unlocking resources held by foreign organisations to these networks is deemed to be important, especially on the long term.

Answering these questions in a more in-depth follow up of this first evaluation of the framework presented here can provide insights into future directions of the further development of the network. These insights can be used in an attempt to influence these directions, if deemed necessary, for instance by adjusting the conditions for entry into the networks.

6. Discussion

In this paper, a framework for the analysis of innovation networks was developed and applied to two cases of policy-driven networks focused on emerging technological fields in the Netherlands. In this framework, elements of network structure as well as network composition were used. The former were derived from literature on social network analysis, while the latter were derived from the literature on the resource-based view of the firm. These two approaches were found to complement each other in regard to addressing aspects that are of importance in evaluating innovation networks.

Based on a literature review, the relationships between the different concepts of network structure and composition and network innovative performance were proposed to be non-linear, implying that both very low and very high values for the corresponding measurements would negatively affect the innovative performance of the network. Using the interviews, this framework of strengths and weaknesses of networks was refined and it was concluded that in emerging networks in high technology fields cohesion is considered to be favourable for innovation. Because of this, management teams of networks are actively stimulating interaction among participants. Centralisation is considered to have a non-linear influence on network innovative performance, as it stimulates focus and continuity, but very high levels of centralisation reduce the overall cohesion of the network. Hence, centralisation needs to be mitigated by a sufficiently high level of overall level of cohesion in the network. In regard to the composition of the network in terms of the resources and strategies of its participants, it can be concluded that partner scarcity, as defined by Dyer and Singh [36], may occur and negatively influence the innovative performance of the network. Also, in order to build trust among partners in an emerging

Table 9
Suggestions for management and policy.

CTMM	Suggestions for management and policy
Limited cohesion	Evaluate: to what extent can additional opportunities for benefiting from synergies be identified between organisations that participate in the network and are not utilized at present?
Overlap of strategies	Evaluate: to what extent this poses a problem for securing fruitful collaboration within the network
BMM	
Lack of leadership	Evaluate: does this relative lack of leadership pose problems for further development of the network in the future?
Limited coverage of some knowledge fields: risk of partner scarcity	Evaluate: are there organisations missing from the network? In what other countries are promising developments going on, and who are important organisations in those countries?

network the extent of overlap of participants' strategies needs to be limited. These findings may be especially relevant for emerging networks, as both cases analysed here concern networks in a very early stage of development. It could be that once the networks gain maturity, some of the effects on innovative performance presented here may change. For instance, in a more mature network trust has accumulated between participants. This may increase the risk of lock-in, as strong ties may have emerged over time [51]. Furthermore, over time it will be clearer who the central organisations are. Consequently, the potential problems with the lack of leadership might decrease over time.

Several limitations of this study need to be mentioned to allow for an adequate interpretation of the findings presented. First of all it needs to be noted that the networks examined only included interorganisational relationships that were a result of projects funded by either the CTMM or the BMM program in their respective first calls for proposals. This implies that many relationships of Dutch organisations that are active in the fields of biomedical materials and translational molecular medicine are not included here. However, using the data on the CTMM and BMM networks, the *contribution* of these government policy initiatives in terms of network formation can be evaluated. It would be interesting to compare this data with data on the other relationships of these organisations. However, such data is not publicly available as organisations are not eager to disclose all their collaborations.

A difficulty of network analysis in general is that it is difficult to make an objective statement on whether a value of a specific measure is too high, too low or just about optimal. This would require extensive further research, and even then it may be that under certain circumstances certain network configurations are more favourable than under other circumstances. To resolve this, the approach that was chosen here was to compare two networks, and determine their *relative* weaknesses and strengths and thereby indicate for each of the networks what its primary policy concerns or questions for further research would be. Another way to deal with this would be to conduct a longitudinal analysis of the developments in network structure and composition. By means of such an analysis, it would be possible to determine if potential weaknesses become even more evident or are mitigated over time. This would also be interesting for further research on policy-driven networks.

Another interesting recommendation for further research concerns taking into account the content of the relations. In other words, that you take into account what the relation really is about. Do partners for instance exchange knowledge or technology? And what are the effects of these different types of relations on the innovative performance of the network? Similarly, what are the effects of strength and intensity of the relations in the network? These questions might be interesting for a further understanding of performance of these innovation networks.

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Tessa van der Valk (PhD) is an Innovation Policy researcher at TNO (Leiden, The Netherlands). She obtained a PhD in the field of innovation studies at Utrecht University, the Netherlands. Her main research interests are innovation network development, interorganisational collaboration and innovation in emerging technology fields.

Maryse M.H. Chappin (PhD) is an assistant professor at the Department of Organization Studies at Tilburg University (Tilburg, The Netherlands). Her research focuses mainly on networks in (environmental) innovation and the relation between environmental innovation and environmental policy.

Govert W. Gijsbers (PhD) is an Innovation Policy researcher at TNO Strategies for the Information Society (Delft, The Netherlands). He completed his PhD research on Networks in agricultural innovation at the Erasmus University of Rotterdam. He specialises in research and innovation policy, with a special interest in planning, monitoring, evaluation and impact assessment. His work includes innovation and foresight studies and he does research on the dynamics of knowledge infrastructures and the changing roles of Research and Technology Organizations in open innovation.