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On the functional and structural scope of technological innovation systems – A literature review with conceptual suggestions

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ABSTRACT

This paper reviews how the functional and structural scope of technological innovation systems (TIS) are understood in the literature. We find that it is often unclear if the system function involves innovation, production or both, and a lack of agreement as to whether structural elements are social or social and technical. Since these issues risk hindering cumulative knowledge development and conceptual advancements, we argue that a clear and shared underlying system model is needed. Taking steps in this direction, we propose that the function of a TIS is to develop and shape a specific technology; that this technology can be understood as a production-consumption system; and that the structural elements of a TIS are social, technical and possibly ecological. In addition, we offer guidance to boundary-setting in empirical case studies. We hope that the paper will inspire continued conceptual development in the TIS community and beyond.

1. Introduction

A major strand of the sustainability transitions literature employs the technological innovation systems (TIS) framework (Markard et al., 2012; Köhler et al., 2019) to analyze the transformation of sectors such as energy (Dewald and Truffer, 2011; Foxon et al., 2010; Jacobsson and Karltorp, 2013; van Alphen et al., 2009; Wieczorek et al., 2013), transport (Hillman and Sandén, 2008; Kivimaa and Virkamäki, 2014; Markard et al., 2009; Suurs et al., 2010), wastewater treatment (Bichai et al., 2018; Binz et al., 2014, 2012) and food (König et al., 2018; Sixt et al., 2018; Tziva et al., 2020). This paper concerns ambiguities and contradictions in the functional and structural scope of the system model underlying the TIS framework. First, the functional scope is generally described in a way that allows for different interpretations, foregrounding an overarching system function related to (i) innovation, (ii) production, or (iii) a combination of the two. Second, there is no consensus about whether the structural scope, as explicitly stated, includes (i) social or (ii) social and technical elements. In addition, there are different interpretations of TIS 'functions',[1] which is the key concept used to identify strengths and weaknesses in the innovation process and thereby inform policymakers and other actors about possible intervention strategies (Bergek et al., 2008a; Borras and Edquist, 2013; Hekkert et al., 2007; Weber and Rohracher, 2012; Wieczorek and Hekkert, 2012).

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[1] We will refer to functional processes used to analyze change as 'functions' (i.e. within quotation marks) throughout the paper, to distinguish this analytical concept from the overarching system function (Section 2).

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These fundamental issues been subject to little debate and few scholars have tried to increase the conceptual rigor. Instead, the TIS community has advanced the framework conceptually in other ways (Bergek et al., 2015; Binz et al., 2012; Dewald and Truffer, 2011; Kern, 2015; Kivimaa and Kern, 2016; Markard et al., 2015; Musiolik et al., 2018; Wieczorek and Hekkert, 2012) and strengthened its foundation through empirical research in different geographical and sectoral contexts (Andersson et al., 2018; Bichai et al., 2018; Foxon et al., 2010; Jacobsson and Karltorp, 2013; Kivimaa and Virkamäki, 2014; Suurs et al., 2010; Tziva et al., 2020), while leaving the underlying system model intact (and often ambiguous).[2] The broad recognition of this literature shows that some level of interpretative flexibility is likely a prerequisite for successful research, particularly on social phenomena such as technological innovation and sustainability transitions.

Nevertheless, we argue that the TIS community would benefit from a clear and shared understanding of the functional and structural scope of the underlying system model. The current lack of precision makes the literature difficult to comprehend for the growing group of scholars, students and consultants that apply the TIS framework.[3] Moving towards a system model that is clear, yet possible to adapt to different lines of inquiry, may therefore broaden and revitalize the TIS community. In addition, a clearer logic would benefit research that develops computer models that simulate the emergence, growth and shaping of socio-technical systems (Holtz et al., 2015; Mirzadeh Phirouzabadi et al., 2022; Walrave and Raven, 2016), support efforts to establish links between innovation studies and technology assessment (Andersson, 2020; Andersson et al., 2021b), and enable the development of a deductive theoretical perspective that clarifies the notion of 'functions'.[4]

The purpose of this paper is therefore to review how the functional and structural scope of TIS are understood and explicitly described in the literature as well as to suggest conceptual clarifications. To that end, we first discuss what it means to apply systems thinking to research on technological innovation and identify different approaches to specifying the functional and structural scope of system models (Section 2). After describing our methodology (Section 3), we proceed to review the literature and identify ambiguities and contradictions (Section 4). We then discuss our findings, take steps towards a more well-defined TIS concept by making three propositions, offer some guidance to boundary-setting in empirical case studies and highlight implications for future research (Section 5). The paper ends with brief concluding remarks (Section 6).

2. The functional and structural scope of system models

The TIS framework is an example of how systems thinking can be applied to studies of technological and industrial change.[5] Systems thinking is associated with a multi-disciplinary movement that emerged in the mid-20th century (Bertalanffy, 1968; Boulding, 1956; Parsons, 1951; Weaver, 1948; Wiener, 1948) and later expanded into the management sciences with the aim of improving the governance of firms, technologies and whole economies (Churchman, 1968; Forrester, 1961; Page, 1967; Simon, 1962; von Foerster, 1960). In the 1980s, innovation systems theories started to branch off from this broader family, in a stream of literature that would eventually result in the TIS framework (Carlsson and Stankiewicz, 1991; Freeman, 1988; Lundvall, 1992; Nelson, 1993). While there is today a plethora of diverse theories and methods based on systems thinking, they share a basic understanding of system models as sets of *interlinked parts that form a unified whole* (Checkland, 1999; Flood and Carson, 1993; Meadows, 2009).

The unified whole of a system model can be defined by one or several functions that describe what role the system plays in its context (Flood and Carson, 1993).[6] This *functional scope* makes it possible to define degrees of goal achievement and use the model to assess strengths and weaknesses (system failures). It also creates a rationale for including some structural elements and relations while excluding others. Other traits of system models are derived from the properties of the parts. Although most system functions depend on a variety of elements, it is common to make an analytical delimitation that excludes certain types of elements based on their own properties, regardless of their contribution to the system function. This *structural scope* is commonly reflected in the names of system models; social systems are made up of human actors and their relations, technical systems consists of physical artifacts and ecological systems of non-human life and its natural environment (Ingelstam, 2012).

Although the real-world interaction of elements certainly gives rise to systemic features, all system models are analytical constructs (Checkland, 1999; Flood and Carson, 1993; Jacobsson and Jacobsson, 2014; Meadows, 2009). Within sustainability transitions research, and most other disciplines that draw upon systems thinking, the rationale for setting system boundaries is rarely developed

[2] The authors of this paper have also contributed to the confusion by publishing TIS papers that fail to clarify the underlying system model. Notably, some of these are reviewed and criticized in this paper.

[3] As two of the authors of this paper can testify from their own experience, it also makes it hard for new scholars to enter the field.

[4] 'Functions' have been referred to as "more or less arbitrary" (Fuchs et al., 2012, p. 12). Although this accurately highlights ambiguities, we do not see 'functions' as arbitrary. Foundational contributions identified key processes through extensive literature reviews (Bergek et al., 2008a; Hekkert et al., 2007) and the resulting typologies have ever since been developed pragmatically in a continuous scientific process. While one may criticize (or praise) the scholarly freedom of this process, it is far from the guesswork suggested by the notion of arbitrariness.

[5] Other systems approaches that address similar phenomena include: innovation system frameworks focused on nations (Freeman, 1988; Lundvall, 1992), regions (Cooke, 2001; Cooke et al., 1997), economic sectors (Malerba, 2002) and societal missions (Hekkert et al., 2020), some of which adopt a functional approach (Edquist, 2004; Johnson and Jacobsson, 2001; Kubeczko et al., 2006) and/or combine sectoral and geographical perspectives (Kubeczko et al., 2006); the multi-level perspective on the dynamics of socio-technical systems of production and consumption (Geels, 2002; Kemp et al., 1998); and the more firm-oriented innovation ecosystem framework (Adner, 2006; Adner and Kapoor, 2010).

[6] The notion of a system function neither suggests that the system is "conscious" and has a "will", nor that its elements must be supportive of, or even be aware of, this function. It simply means that an observer may define a system in relation to properties that constitute a function, or potential function, in its context.

from scratch when advancing theory or embarking on empirical investigations. Instead, analytical frameworks offer guidance by defining system models that foreground different types of system functions (functional scope) and structural elements (structural scope), which may also be restricted to a specific type of spatial region, e.g. global, national or regional (spatial scope) and time period, e.g. long or short, historic or future (temporal scope). In this paper, we are concerned with issues related to how the functional and structural scope of the system model underlying the TIS framework. To frame this discussion, the following two sections will outline different approaches to defining the functional and structural scope when the phenomenon of interest is technological innovation.

2.1. The functional scope of system models focused on technological innovation

While system models of technological innovation can be constructed in many different ways, we see three main approaches to defining their functional scope. The differentiation is based on the distinction between production and consumption, defined as the creation and use of many identical or next to identical outputs (goods and services), and innovation, defined as the creation or transformation of one or several unique outputs.

The first approach defines the functional scope in relation to the utilization of technology in processes of production and consumption. This results in a system that repeatedly combines means to ends in a (value) chain where intermediate products are created and consumed, and final products are provided to some market where they are consumed (Andersson et al., 2021b; Arthur, 2009; Sandén and Hillman, 2011). For the sake of brevity, we will initially refer to this type of system as a ‘production system’ and return to the notion ‘production-consumption system’ in Section 5. Although the technological process which defines a production system can be conceived of at vastly different scales, the TIS literature is generally concerned with meso-level perspectives (Köhler et al., 2019). A system model with a functional scope focused on the utilization of technology in production and consumption processes thus delineates what could in layman terms be described as an industry and its market.

The second approach instead defines the functional scope in relation to the development of technology in processes of innovation. This results in a system of innovation that transforms how means are converted to ends in society. Notably, the term ‘innovation system’ can be used for systems that develop one or several specific technologies or for systems that develop any new (and unspecified) technology.

The third approach defines the functional scope by combining the development and utilization of technology within the same system model. This results in a system of production and innovation with a dual function that involves both the repeated conversion of different means to specific ends in a given technological process and the transformation of this technological process. This way of combining production and innovation within the same system model is likely equivalent to what Malerba (2002) refers to as ‘sectoral systems of innovation and production’.

The existence of the third category, with its dual and less clear-cut functional scope, indicates a possible underlying additional rationale for system delineation, which could stem from an implicit structural starting point. For example, if an analyst a priori includes a group of firms active in a technological field, a likely finding is that many of these are involved in both production and innovation, and hence the analyst is tempted to develop a system model with two system functions. This might be called an actor-centric approach (or, more generally, ‘structure-centric’), as opposed to technology-centric (or ‘function-centric’’) approaches that take technology as the only starting-point.

The three approaches to defining the functional scope will form the basis for the review presented in Section 4 and be referred to by the codes ‘F-P’, ‘F-I’ and ‘F-PI’ (Table 1). Note also that they have important consequences for the analysis of TISs. If the functional scope is derived from production (and consumption), what is interesting is *change of the TIS*. Conversely, if the functional scope is derived from innovation, it is *change achieved by the TIS* that is of interest. If instead the functional scope is derived from both production and innovation, the two perspectives are combined (or muddled) and what becomes interesting is *change of and by the TIS*.

2.2. The structural scope of system models focused on technological innovation

Technological innovation is an empirical phenomenon that involves social elements such as actors and institutions, technical elements such as physical artifacts, machines and infrastructure, as well as natural resources and other elements associated with the natural environment. However, this does not necessarily mean that the structural scope of system models used to study technological innovation must cover all these domains. On the contrary, it is possible to define system models that focus on any combination of elements and thereby capture different aspects (Andersson, 2020). For example, innovation ecosystems consist of networks of organizations (Adner and Kapoor, 2010), while the niches and regimes subject to analysis in studies based on the multi-level perspective are (at least in foundational texts) described as institutional rule-sets (Rip and Kemp, 1998). These approaches accordingly restrict the

Table 1
Three approaches to defining the functional scope of system models focused on technological innovation.

Functional scope	Included processes and activities	Analytical focus	Code
Production	Utilization of technology in processes of production and consumption	Change of the system	F-P
Innovation	Development of technology in processes of innovation	Change achieved by the system	F-I
Production and innovation	Development and utilization of technology in processes of production and consumption, and innovation	Change of and by the system	F-PI

structural scope to different types of social elements. In contrast, the notion of socio-technical systems of production and consumption, which is central to sustainability transitions research (Köhler et al., 2019), has a broader structural scope that also includes technical elements, but still exclude natural resources and other elements associated with the natural environment (Ahlborg et al., 2019; Andersson, 2020; Olsson et al., 2014).

For the purposes of our review, we settle for a broad distinction between two approaches to defining the structural scope (Table 2). One that only includes social elements, referred to by the code 'S-S', and another that includes both social and technical elements, referred to by the code 'S-ST'.

It should be emphasized, finally, that excluding a type of structural element from a system model does not necessarily prevent an analyst from accounting for the characteristics and influence of this type of structural element in other ways. This is shown by the large number of studies that investigate technological innovation and sustainability transitions using analytical approaches based on system models with a structural scope limited to social elements. While these studies do not explicitly include technology and the environment as parts of the system structure, they (often but not always) account for these domains in descriptions of the system context or implicitly through the lens of actors and institutions. This implies that our distinction between social and socio-technical approaches to defining the structural scope should not be seen as a way to assess whether studies at all have accounted for the role of technology (of course all TIS studies pay attention to technology). Instead, the distinction serves to highlight which types of structural elements that are explicitly included in the underlying system model used to guide the analysis. Arguably, this is an important aspect of an analytical framework such as TIS, since what is explicitly considered in a system model influences what is empirically observed and how the observations are interpreted.

3. Methodology

Based on the theoretical discussion offered in the previous section, the next section reviews the TIS literature. We focus on two questions related to the system model underlying the TIS framework: (i) is the system function production (and consumption), innovation or a combination of the two (functional scope); and (ii), does the system consist of social or social and technical elements (structural scope)? To highlight what the literature indicates with respect to these questions, we use the codes provided in Tables 1 and 2.

The review was carried-out in two steps. First, we performed a close reading and qualitative analysis of five 'foundational papers'. The reason we choose this term is that these are the most cited publications by scholars that develop and apply the TIS framework, which indicates an important influence on the subsequent literature.

Second, we collected all scientific publications using the term 'technological innovation system'. The search was performed in Scopus, initially on June 25th 2019 with a complementing round on September 2nd 2021, based on title, abstract and keywords, and used the specific search term 'technological innovation system'. This resulted in 366 publications, out of which 275 were categorized as articles and reviews, and 91 as conference contributions, books and other publication types. From these search results, we defined and collected a corpus of 229 publications. The corpus was limited to articles and reviews published between 2009 and 2020 in peer-revied journals, and also excluded publications that did neither develop nor use the TIS framework (but rather some other concept or approach associated with the term). The collected publications were then read to quantitatively assess the extent to which scholars include social or social and technical elements in TIS. A similar attempt was made to quantitatively assess how the functional scope is defined, but due to the abounding ambiguity in the literature, this turned out to be difficult to pursue at scale. Instead, a few clear examples were collected as evidence of diverging understandings. In addition to the quantitative analysis, a sub-set of the corpus was read in more detail to inform the discussion about how the foundational papers have been interpreted and further developed by the subsequent literature.[7]

4. A review of the functional and structural scope of technological innovation systems

In this section, we first review five foundational TIS papers and then turn to the growing literature that uses these papers as the main frame of reference.

4.1. *The functional and structural scope of TIS as defined in foundational papers*

The TIS concept was first introduced in a foundational paper by Carlsson and Stankiewicz (1991), even though they actually used the term 'technological systems' (Table 3). Throughout the 1990′s and early 2000′s, the concept was further developed and used in numerous empirical studies, mainly by researchers in Sweden (Carlsson et al., 2002). It was also combined with an approach based on 'functions' (Johnson, 2001, 1998; Johnson and Jacobsson, 2001), which would later be further developed by TIS scholars and in the broader innovation systems literature (Edquist, 2004; Kubeczko et al., 2006). However, these publications are not widely cited by scholars that develop and use the TIS framework.

In the early 2000′s, the TIS concept had also attracted the attention of Dutch and Swiss scholars. They exchanged ideas with their Swedish colleagues, both at conferences and in some joint projects. This resulted in four additional foundational papers published in

[7] The review was also informed by the authors' accumulated experience from years spent applying and developing the TIS framework.

Table 2
Two approaches to defining the structural scope of system models focused on technological innovation.

Structural scope	Types of elements included in the system	Types of elements excluded from the system	Code
Social	Actors and institutions	Physical artifacts (designed objects, machines, infrastructure); Natural resources and other elements associated with the natural environment	S-S
Socio-technical	Actors and institutions; Physical artifacts (designed objects, machines, infrastructure)	Natural resources and other elements associated with the natural environment	S-ST

Table 3
System descriptions in five foundational publications on technological innovation systems.

Publication	System description
(Carlsson and Stankiewicz, 1991)	"A technological system may be defined as a network of agents interacting in a specific *economic/industrial area* under a particular *institutional infrastructure* or set of infrastructures and involved in the generation, diffusion, and utilization of technology. Technological systems are defined in terms of knowledge/competence flows rather than flows of ordinary good and services." (Carlsson and Stankiewicz, 1991, p. 111)
(Bergek et al., 2008a)	"The components of an innovation system are the actors, networks and institutions contributing to the overall function of developing, diffusing and utilizing new products (goods and services) and processes" (Bergek et al., 2008a, p. 408) ""TISs do not only contain components exclusively dedicated to the technology in focus, but all components that influence the innovation process for that technology" (p. 409)
(Bergek et al., 2008b)	"The components of a technological innovation system are the actors, networks and institutions contributing to the development, diffusion and application of a particular technology […]. In line with a number of previous authors […], we also include the technology as such among the components." (p. 576) "[a TIS] focuses on the innovative activities within [a broader system that includes production and consumption activities]" (p. 576)
(Hekkert et al., 2007)	"[a technological system is] a network of agents interacting in the economic/industrial area under a particular institutional infrastructure […] and involved in the generation, diffusion, and utilization of technology. […] it is useful to think in terms of technological systems as a special version of innovation systems. A technological system is a combination of interrelated sectors and firms, a set of institutions and regulations characterizing the rules of behavior and the knowledge infrastructure connected to it." (p. 416)
(Markard and Truffer, 2008)	"a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product." (p. 611)

2007 and 2008, which are widely cited in TIS studies: two where the Swedish researchers (Bergek et al., 2008a, 2008b) propose an analytical framework based on 'functions'; one where the Dutch researchers (Hekkert et al., 2007) present a slightly different version of this 'functions' approach; and one where the Swiss researchers (Markard and Truffer, 2008) arrive at the TIS concept as a way to integrate separate research strands dealing with innovation systems and technological transitions.[8]

While scholarly interaction explains similarities across the foundational papers, there are also areas where they are vague or in disagreement. This is evident in how the TIS concept is described (Table 3), but also relates to more subtle conceptions of the functional and structural scope that will be further discussed below.

4.1.1. Functional scope

The foundational papers define TISs in quite similar terms – as systems that generate, develop, diffuse, utilize and/or apply technology (Table 3) – which indicates a broad functional scope that includes both production and innovation (F-PI). However, a detailed review reveals differences and ambiguities in how the functional scope is understood.

To begin with, the first paper by Carlsson and Stankiewicz (1991) is rather vague. On the one hand, the authors portray a technological system as similar to a national innovation system, albeit one that transcends national borders, focuses on one part of the economy (a techno-industrial domain) and pays more attention to micro-level developments. They also propose that the system should be "defined in terms of knowledge/competence flows rather than flows of ordinary good and services" (Carlsson and Stankiewicz, 1991, p. 111). This suggests a functional scope focused on innovation (F-I). On the other hand, the authors refer to the utilization and exploitation of technology, and refrain from restricting the system to innovation, which implies that established practices and products are in fact included as well. A possible interpretation is that the authors understand technological systems as a container in which new technologies are both generated and exploited (F-PI). This is in line with the proposed system definition as well as the authors' focus on a loosely defined economic/industrial area rather than one or several well-defined technologies. The idea of a 'container' here refers to the fact that the analytical interest is not in how this industrial area changes or what it achieves, but rather in what is done within it. Put differently, the system seems to be defined by a network of actors, rather than the function they fulfill. This corresponds quite clearly to the actor-centric approach described in Section 2.

The four later papers (Bergek et al., 2008b, 2008a; Hekkert et al., 2007; Markard and Truffer, 2008) advance and concretize the TIS

[8] The Dutch scholars were inspired by the earlier work by Bergek and colleagues (Johnson, 2001, 1998; Johnson and Jacobsson, 2001). Note also that Johnson was Anna Bergek's maiden name.

concept in several ways. For starters, the term innovation is added to Carlsson and Stankiewicz (1991) notion of technological systems, and the resulting TISs are defined with reference to new products and processes (Table 3). This clarifies the focus on novelty and innovation, rather than any techno-economic activity. TISs are also more explicitly portrayed as focused on a specific technology, delineated in terms of a product/artefact or a knowledge field. In addition, the development, diffusion and use of technology is described as a phenomenon that is achieved by, rather than occurs within, the system. In contrast to Carlsson and Stankiewicz (1991), this indicates a more technology-centric perspective.

At the same time, ambiguity persists when it comes to the more specific functional scope. The four papers define TIS with reference to the utilization or application of technology, which indicates that not only innovation but also production is seen as a part of the system function (F-PI). This is also suggested by Bergek et al. (2008a) when they argue that a "TIS may be able to 'change gear' and begin to develop in a self-sustaining way as it moves into a growth phase" (p. 420), which seems to identify the system with a growing industry and its related innovation activities.

Meanwhile, other parts of the four papers point in the opposite direction. Based on Malerba's (2002) discussion of sectoral innovation systems, Markard and Truffer (2008) make the important observation that the same network of agents can be involved in both production and innovation. While conceding that the "distinction between production systems, incremental innovation processes and radical innovation structures is mostly not very clear-cut" (Markard and Truffer, 2008, p. 610), they argue that the TIS concept should be restricted to radical innovation processes, and not used to describe and analyze neither production nor incremental change. In addition, they highlight that this implies that "a TIS begins at some point in the formative phase and ends at some point in the growth phase" (Markard and Truffer, 2008, p. 611). These ideas very clearly suggest a functional scope focused on innovation (F-I).

A different way to make the functional scope explicit is offered by Bergek et al. (2008b), who distinguish between a TIS and a broader system that describes how a societal function related to a specific technology is fulfilled (through activities of innovation, production and consumption), and confine the TIS to the innovative activities within the latter. This clearly restricts the functional scope to innovation (F-I).

While Hekkert et al. (2007) do not offer much explanation of the functional scope beyond the system description, which includes the application of technology and thus leaves ample room for interpretation (Table 3), it should be noted that they cite Lundvall's (2001) claim that "it is useful to think in terms of technological systems as a special version of innovation systems" (Hekkert et al., 2007, p. 416). This indicates that their conception of TIS also focuses on innovation (F-I).

Most importantly, however, the 'functions' approach offers important clues about the functional scope. Bergek et al. (2008a) define 'functions' as processes "which have a direct and immediate impact on the development, diffusion and use of new technologies, i.e. the overall function of the TIS as defined above" (p. 409). Based on an extensive literature review, they also establish a typology of seven such 'functions'. Bergek et al. (2008b) take the conceptualization further as they propose that 'functions' are processes that "influence the build up of system structures" (p. 578), while Markard and Truffer (2008) describe them as sub-functions to the overarching system function. A contrasting perspective is offered by Hekkert et al. (2007), who view 'functions' as a way to categorize activities and events in innovation systems,[9] but they nevertheless derive a 'functions' typology that is strikingly similar to the one offered by Bergek et al. (2008a). What makes this relevant for the functional scope of TIS is that the 'functions' typologies describe processes associated with the development rather than utilization of technology. No matter the exact conceptual interpretation of 'functions', this clearly suggest a functional scope focused on innovation (F-I).

It should also be noted that the foundational papers differ in their view of boundary-setting in relation to a given functional scope. For example, Bergek et al. (2008a) suggest that "TISs do not only contain components exclusively dedicated to the technology in focus, but all components that influence the innovation process for that technology" (p. 409). This represents a broad view where TIS boundaries are set to include most if not all elements that are decisive for innovation. In contrast, Markard and Truffer (2008) propose narrow boundaries that only include elements that are closely related to, and supportive of, the innovation process. They also argue that a broader view is problematic since "including 'all important factors' means that no distinction is made between those influences, which are closely related to the innovation process and part of potential feedback loops, and those that are not affected by the innovation process" (p. 601), and that including also negative influences would make the concept "degenerate into a merely descriptive bracket for very different processes and structures [and that as] a consequence, it would lose almost every explanatory power." (p. 610).[10]

To summarize, several aspects of the foundational papers suggest that the authors understand TISs as systems focused on innovation (F-I). However, the way the TIS concept is defined, described and discussed is ambiguous. In turn, this opens up for different interpretations of the functional scope.

[9] This stands in contrast to Bergek et al. (2008a), who rather emphasize that any activity or event can contribute to several sub-processes in the overarching innovation process. The difference is even clearer when compared to Bergek et al. (2008b), where 'functions' are defined based on their effect (new structure) rather than on their cause (activities). In fact, Markard and Truffer (2008) explicitly argue against interpreting 'functions' as activities or events, and rather describe them as "emergent properties of the interplay between actors and institutions." (p. 597).

[10] The boundary setting proposed by Markard and Truffer (2008) relates to different ways of combining production and innovation as two functions within the same system model. The system can then either be understood as consisting of all elements that influence either of the two functions (the union), or as the smaller group of elements where each element influences both functions (the intersection). The latter can be viewed as a subcategory of F-I that adds an additional restriction; for a factor to be included, impacting innovation is not enough, it should also be impacted, hence being part of the changing production system.

4.1.2. Structural scope

The foundational papers exhibit similarities with respect to the structural scope as well. When describing the constituent parts of TISs, actors are foregrounded as central elements together with the different types of networks that enable them to interact. The foundational papers also make an a priori exclusion of system elements associated with the natural environment. However, there are also differences. Carlsson and Stankiewicz (1991) highlight networks of agents as the main structural elements, while institutions are treated as given and somewhat static, rather than interdependent and interacting parts of the system. They thus seem to imagine a social system (S-S) without institutional and technical elements. This narrow view of the structural scope is broadened in the later foundational papers, which clearly describe institutions as a core part of the TIS structure (Bergek et al., 2008b, 2008a; Hekkert et al., 2007; Markard and Truffer, 2008) and thus acknowledge dynamics, not only among actors, but also between actors and institutional elements.

When it comes to technical elements, however, there is both disagreement and ambiguity across the later foundational papers. A clear position is offered by Hekkert et al. (2007) who first defines TIS as "a combination of interrelated sectors and firms, a set of institutions and regulations characterizing the rules of behavior and the knowledge infrastructure connected to it" (p. 416) and later simplify their view of system elements to actors, networks and institutions. Referring to Carlsson and Stankiewicz (1991), they also point out that the term technological system is used by scholars that study large technological systems (LTS), and that this literature includes physical artifacts as system elements (Hughes, 1987). This leads Hekkert et al. (2007) to adopt the term Technology Specific Innovation Systems, as a way to highlight that their system only includes social elements (S-S) (this term was in later publications abandoned in favor of TIS).

Bergek et al. (2008a) and Markard and Truffer (2008) also define and describe TISs as systems that consist of actors, networks and institutions (S-S). Nevertheless, Bergek et al. (2008a) in one place explicitly identify TISs as "socio-technical systems" (p. 408), which adds ambiguity regarding the status of technical elements. This issue is in fact addressed by Markard and Truffer (2008) who discuss whether the innovation as such, which most often has a partly technical character, should be included in the innovation system. As they put it: "We think that [this] has to be seen as an analytical choice. In reality, the results of the innovation process feed back directly into its determinants. Due to this close and critical interaction we suggest to regard the innovation itself as a part of the system, a part that is not genuinely different from other system elements except from the fact that it is the element an innovation researcher might be most interested in studying" (p. 599–600). This indicates an openness to both social and technical elements, and thus suggests a broader structural scope (S-ST).

The idea of including both social and technical elements is made most clear by Bergek et al. (2008b). In their view, technology should be included as a system element and given a similar status as actors, networks and institutions, which makes TISs explicitly socio-technical (S-ST).

To summarize, the dominant viewpoint in the foundational literature seems to be that TISs consist of actors, networks and institution (S-S). However, there are also ambiguities and contradictions, particularly since one paper explicitly views the system as socio-technical (S-ST).

4.2. How the growing literature interprets the functional and structural scope of TIS

The papers discussed above have become the foundation for a steadily growing research field. Many theoretical aspects of the TIS framework have also been further developed. Addressing the geographical dimension (spatial scope), scholars have highlighted the importance of spatial dynamics and criticized studies that limit their attention to a particular region (Binz et al., 2014; Coenen, 2015; Coenen et al., 2012; Hansen and Coenen, 2015), while proposing complementary analytical frameworks that capture multi-scalar interactions among spatially coupled innovation systems (Bento and Fontes, 2014; Binz et al., 2012; Binz and Truffer, 2017; Gosens and Lu, 2013; Quitzow, 2015). Other scholars have refined the understanding of several 'functions', explored their influence on innovation dynamics, and suggested new processes to complemented existing typologies (Andersson et al., 2021a; Bergek, 2019; Binz et al., 2015; Dewald and Truffer, 2011; Kivimaa and Kern, 2016; Perez Vico, 2014). Yet others have engaged with conceptual development in relation to policy instruments that address system weaknesses (Kivimaa and Kern, 2016; Wieczorek and Hekkert, 2012), the influence of contextual structures on system dynamics (Bergek et al., 2015; Hojcková et al., 2020; Wirth and Markard, 2011), the directionality of TIS development (Andersson et al., 2021b; Yap and Truffer, 2019) as well as the role of agency, resources and system-building (Kern, 2015; Musiolik et al., 2018). Although this has certainly improved the TIS framework, it has generally not addressed the conceptual issues in focus of this paper. Nevertheless, the literature indicates that there has been some development of how scholars understand the TIS concept, and this will be further discussed below.

4.2.1. Functional scope

In general, few publications engage with conceptual discussions about the system function. An exception is Jacobsson and Jacobsson (2014), who describe the TIS framework as a system model, discuss interpretations of the word "function", and address some issues arising from connotations related to certain traits of sociological functionalism, including the role of agency, intentionality and conflict. However, they focus on the 'functions' concept and do not engage with ambiguities regarding the functional scope. In fact, most TIS studies do not specify the system function beyond references to the foundational literature. This implies that the ambiguities discussed in Section 4.1.1 persist. Nevertheless, it is possible to discern two different interpretations.

On the one hand, some scholars clearly describe a functional scope focused on innovation (F-I). For example, Sandén and Hillman (2011) suggest that the growth of a production and consumption system can "be described by some 'innovation system functions' that relate the growth (or decline) of the elements of the system (and emergent system properties) to the system itself and to external forces"

(Sandén and Hillman, 2011, p. 409). They thus make a sharp distinction between systems of innovation and production, arguing that the former create the latter. In a similar vein, Bergek (2019) acknowledges the difference between an innovation system, a production system and a distribution-market system, suggesting that a TIS is an example of the former since its "nature and boundaries [...] should be defined in terms of problem-solving networks rather than buyer-supplier relationships" (p. 202).

On the other hand, other scholars seem to interpret TIS as a system model that also includes the use of technology (F-PI), even though this choice is rarely motivated and fully explained. The view does, however, become apparent when contributions describe TISs as industries (Kushnir et al., 2020; Mäkitie et al., 2018; Markard et al., 2020) or organize system elements as value chains (Andersson et al., 2018; Stephan et al., 2017). Moreover, the way conceptual development related to TIS context is carried-out points in a similar direction. For example, Bergek et al. (2015) offer an extensive discussion of context, without making any reference to industries and markets where the focal technology is utilized. If the functions these represent were not imagined to be a part of the TIS, they should be captured by important contextual structures. In fact, it is generally uncommon that the TIS construct is complemented with an additional system (or other entity) that does in fact utilize the focal technology in production processes. Also, it is in most empirical studies possible to replace the term 'TIS' with 'industry' or 'sector', without any apparent loss of meaning and arguably with a clearer exposition as a result.

In addition to these two main interpretations, there a few publications where TISs are described in a way that suggests a system function focused exclusively on production (F-P). For example, Markard et al. (2020) define a "nuclear TIS" in terms of the "actors, institutions, networks, and technology involved in the specific activity of reactor construction" (p. 3), while Tziva et al. (2020) describe mature TISs as systems that "deliver standardized products across mass markets" (p. 218). This links TIS to standardized production processes that are very different from the innovation processes through which they were at some point developed. However, examples of this view are both vague and few, and we acknowledge that the authors may perceive TIS differently than what these descriptions suggest.

The widespread ambiguity prevents a quantitative assessment of how widespread the viewpoints discussed above are. In Table 4, we instead provide a few typical quotes from publications that seem to interpret the functional scope of TISs in terms of either innovation (F-I) or (some combination of) production (F-P) and/or production and innovation (F-PI). Notably, the ambiguity also prevents us from distinguishing the two latter categories (F-P and F-PI).

Lastly, ambiguities regarding the functional scope have been inherited to the concept of 'functions'. Most publications either directly, or by reference to foundational literature, describe 'functions' as a way to decompose the overarching system function into a typology that enables a dynamic analysis. This idea is often expressed by referring to 'functions' as sub-processes to the wider innovation process, while some describe them as "intermediate variables between structure and system performance" (Jacobsson and Bergek, 2011, p. 46). But since the overarching system function is most often unclear, it remains ambiguous what 'functions' actually describe. Other publications go further and argue that 'functions' in fact contribute to the build-up of system structure, but since it is rarely stated in which system this structural build-up occurs, the ambiguity persists. Given that most would agree that 'functions' are an attempt to describe different aspects of innovation, which in turn can be understood in terms of structural change of some system, the unresolved question seems to be of what system(s).

4.2.2. Structural scope

When it comes to the structural scope, many scholars maintain a focus on social elements (S-S) in explicit definitions of the underlying system model and account for infrastructures and other material elements indirectly or as contextual factors (Bento and Fontes, 2014; Binz et al., 2014; Coenen et al., 2012; Dewald and Truffer, 2011; Gosens et al., 2015; Kushnir et al., 2020; Markard, 2020; Musiolik et al., 2018; Yap and Truffer, 2019). At the same time, the idea of including technical elements in the system model (S-ST), proposed by Bergek et al. (2008b), has been adopted in numerous studies (Hojcková et al., 2020; Mäkitie et al., 2018; Sandén and Hillman, 2011; Stephan et al., 2017; Suurs and Hekkert, 2009; Wieczorek and Hekkert, 2012). In 2015, leading scholars from the groups behind the foundational literature in a joint paper defined a TIS as a "set of elements, including technologies, actors, networks and institutions, which actively contribute to the development of a particular technology field" (Bergek et al., 2015, p. 2), which clearly indicates that the socio-technical view had become widely established (S-ST).

However, both views are still common in the literature, with some leading scholars changing definitions back and forth in different publications. This suggests that the TIS community considers the treatment of technical elements as an explicit category to be an analytical choice rather than a fundamental part of the analytical framework. This is acknowledged by Jacobsson and Bergek (2011), who also assert that technology can be treated "as knowledge embodied in actors and as outputs of the system (codified knowledge and artefacts)" (p. 45) when it is not included as a separate structural element.

At the same time, a fair share of TIS publications is ambiguous or even contradictory (e.g. by describing the system as socio-technical while only specifying social elements). A quantitative assessment (Fig. 1) shows that with an increasing number of papers, there is no consensus and the level of clarity is not increasing.

To conclude, it is apparent that the basic tenets of the TIS framework have remained intact since its inception. Consequently, fundamental ambiguities and contradictions have been left largely unresolved. This is shown by the fact that most studies still limit their frame of reference to the foundational literature and use more or less the same concepts as the ones proposed in these publications.

5. Discussion with suggestions for future research

In this section, we discuss how some of the conceptual issues revealed by our literature review can be resolved. Our propositions

Table 4
Examples of different interpretations of the functional scope of TIS. Ambiguity prevents us from distinguishing the two rightmost categories (F-P and F-PI).

<table>
<tr><th>F-I: The functional scope of a TIS captures the development of technology in processes of innovation</th><th>F-P: The functional scope of a TIS captures the utilization of technology in processes of production (and consumption)</th><th>F-PI: The functional scope of a TIS captures the development and utilization of technology in processes of innovation and production (and consumption)</th></tr>
<tr><td>“This means that the innovation process takes place within a system comprised of different actors who contribute to the overall goal of the innovation system: the development and diffusion of the innovation in question.” (Rojon and Dieperink, 2014, p. 395)
“Recent insights suggest that TIS facilitates the creation of markets and the development of entrepreneurial activities around technologies by fulfilling key activities and processes…. It follows that diffusion of technologies would be enabled by improved functional performance of the relevant TIS” (Tigabu et al., 2015, p. 332)
“The TIS is the systemic description of how [a production system] emerge, develop and expand.” (Andersson et al., 2017a, p. 143)
“The expected results of technological innovations systems are an improvement of or a new product, process development activities, and market development or service improvement activities” (Sambo and Alexander, 2018, p. 3)
“we […] call the growing system a ‘technological system’, reserving the term ‘technological innovation system’ for the model describing and explaining the growth process.” (Hojcková et al., 2020, p. 2)</td><td colspan="2">“We use the term “nuclear energy technology” to refer to the commercial use of nuclear for power generation, and “nuclear TIS” (or “nuclear industry”) for the actors, institutions, networks, and technology involved in the specific activity of reactor construction.” (Markard et al., 2020, p. 3)
“TISs in a mature state are highly structured systems that deliver standardized products across mass markets” (Tziva et al., 2020, p. 218)
”[…] appropriately describe the formative stage as one where accumulation of many small changes begins to form a new entity, industry or TIS.“ (Jacobsson, 2008, p. 1494)
“[…] we apply a value-chain perspective to TISs. We include all (vertically and horizontally) related parts of the value chain into our conceptualization of a TIS, which represents an integrated approach. This approach proposes a clear definition of the boundaries of a TIS that considers the fact that many technologies are developed, produced and used across sectors, and allows TIS to be delineated from sectoral systems of innovation.” (Stephan et al., 2017, p. 710)
“Recent studies have shown that established sectors can indeed exercise significant influence on an emerging TIS, understood here as a nascent industry.” (Mäkitie et al., 2018, p. 814)</td></tr>
</table>

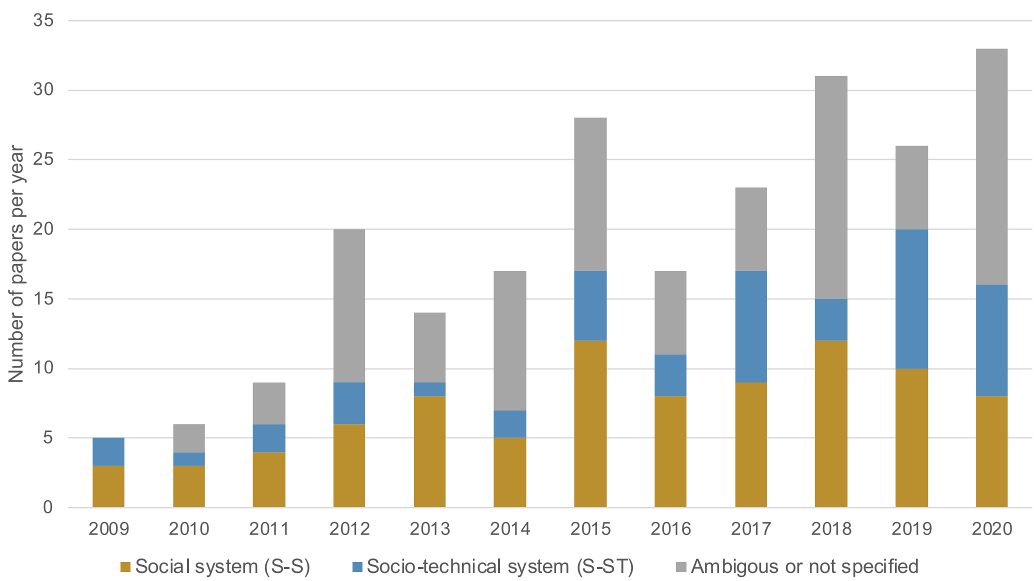

Fig. 1. A quantitative assessment of how the structural scope of TIS is stated in 229 TIS papers published between 2009 and 2020.

should not be seen as a final solution, but rather as a starting point for continued efforts to increase clarity and rigor through scientific dialog. From summing up identified issues (Section 5.1), we move on to suggest a new definition of TIS as a general model (Section 5.2), discuss what needs to be defined in each case study that employs this model (Section 5.3), and highlight some avenues for further research (Section 5.4).

5.1. Ambiguities, contradictions and the need for clarification

Although TIS studies often remain ambiguous with regards to the functional scope, two widespread interpretations can be identified: one that limits the system to the development of technology through innovation processes (F-I); and another that also includes the utilization of technology in production and consumption processes (F-PI). Put differently, some regard it as a traditional innovation system focused on a specific technology, whereas others associate the system with an existing or emerging industry (and market) and its related innovation activities. In addition, there are a few examples of publications that seemingly suggest a functional scope limited to the utilization of technology in production and consumption processes (F-P). These are, however, both vague and few.

Regarding the structural scope, some scholars understand the system as social and describe its elements in terms of categories such as actors, networks and institutions (S-S), while others include technology as an explicit category by referring to technical artifacts and knowledge or physical infrastructure as additional elements (S-ST). On top of that, many TIS studies are ambiguous and do not specify how they conceptualize system structure.

In our view, evolving understandings can be viewed as a natural part of the scientific endeavor and is not problematic per se. The identified interpretations of the functional and structural scope of TIS are arguably reasonable points of departure for research on technological innovation. What is troublesome is rather that they refer to the same concept (TIS). This, together with the fact that many publications do not explicitly define the functional and structural scope beyond references to foundational papers, creates an ambiguity that we believe has negative consequences. For starters, it makes it difficult to understand how scholars that apply the TIS framework set system boundaries, since the logic behind the inclusion or exclusion of a particular element is based on its relation to the system function. This reduces the comparability of TIS analyses and thereby hinders cumulative knowledge development. Moreover, the ambiguity impedes conceptual advancements, particularly related to the key concept of 'functions'. Although the TIS literature testifies to the practical usefulness of current 'functions' typologies, it remains unclear how the change processes they refer to should be understood theoretically. This implies that efforts to increase the rigor of functional assessments, create formal system models and develop complementary deductive typologies of 'functions', all stand on quite lose ground.

5.2. Towards a more well-defined TIS concept

When advancing towards a more well-defined TIS concept, a fruitful starting point is our general definition of innovation as the creation of something new (Section 2). This definition makes it reasonable to suggest that TISs create new technology and we therefore make the following first proposition:

Proposition 1. *A technological innovation system (TIS) is a set of structures and processes that are unified by their role in developing and shaping a specific technology.*

The proposition makes explicit that the functional scope of TISs is to develop and shape technology through processes of innovation (F-I). It also emphasizes that innovation is not only about the development and diffusion of novel technologies, but also about shaping the transformation (and possible decline) of existing technologies. In addition, it limits the TIS concept to the development and shaping of a specific technology. This implies that the TIS framework should not be used to study any technological innovation activity that a network of actors happens to engage with (i.e. an actor-centric approach). The point of departure should rather be an interest in innovation related to a well-defined technology (i.e. a techno-centric approach).[11]

The focus on a specific and well-defined technology underlines the need for TIS studies to clearly describe the technology subject to analysis. Although technology can be understood in different ways, it is fundamentally about the conversion of means to ends (Arthur, 2009). This implies that the technology which is developed and shaped by a TIS can be understood as a production system (Section 2). This production system is made up of many subprocesses and subsystems (i.e. technologies at a lower system level), in which intermediary products are created and consumed. Observed from another perspective, the production system can thus be called a consumption system. More inclusively, we may then speak about production-consumption systems and, as will be further discussed in the next section, use this construct to specify the technology in focus. This leads to our second proposition:

Proposition 2. *The specific technology, which is developed and shaped by a technological innovation system, can be understood as a production-consumption system.*

We may thus view a TIS as a system that develops and shapes a production-consumption system.[12] This means that a conceptual link opens to other approaches to sustainability transitions, such as the multi-level perspective, which focus on socio-technical systems of production and consumption (Geels, 2005, 2004). The functional scope proposed here allows the TIS framework to be used in studies that investigate the development and shaping of production-consumption systems at different levels (e.g. niche and regime). This stands in contrast to previous attempts to integrate the MLP and TIS framework (e.g. Markard and Truffer (2008)), which primarily link TISs to niche developments.

The conceptual link between TISs and production-consumption systems also facilitates efforts to attend more to the directionality of innovation processes, since the change resulting from processes in TISs can be conceptualized in terms of transformed configurations of production-consumption systems (Andersson et al., 2021b). This is arguably a more rigorous and comprehensive approach than merely distinguishing between different technological alternatives.

In addition, the conceptual link makes it possible to clearly define 'functions' as a decomposition of the overarching system function, which makes much sense theoretically given that developing and shaping a production-consumption system involves sub-

[11] This is not to say that it is of no interest to study predefined groups of actors and their innovation activities, but rather that such studies should use another analytical framework.

[12] The development of a production-consumption system at one level implies the shaping of a production-consumption system at a higher level.

processes such as knowledge development, legitimation and market formation. In turn, this provides a theoretical basis for deductively developing the 'functions' approach, which may complement the inductive basis on which current typologies rest. A possible starting point for such a deductive approach could be the build-up and transformation of the different structures required for a production-consumption system to exist and function (Andersson et al., 2017b; Bergek et al., 2008b; Sandén and Hillman, 2011).[13]

Furthermore, we would argue that it is advisable to explicitly include both social and technical elements (S-ST) in the structural scope of TISs as well as their associated production-consumption systems. As noted in Section 2.2, we acknowledge that the role of technical elements could be partly captured through descriptions of a system context or indirectly through the lens of actors and institutions (as suggested by Jacobsson and Bergek (2011)). However, we do believe that important perspectives on the innovation process may pass unnoticed if technical elements are excluded or only considered as an implicit category. Just like social institutions, the material aspects of technology are not only created in the interaction of agents, but also constitute factors that enable and constrain their behavior. Technical elements such as artifacts and knowledge are also to some extent independent of specific actors and are therefore not easily captured merely as implicit subcategories.[14]

In fact, we find it reasonable to also allow for the inclusion of ecological (biological and geophysical) elements.[15] Factors associated with nature clearly influence technological innovation processes,[16] particularly in sectors such as food, forestry and mining that draw directly on natural resources and ecosystem services (Andersen and Wicken, 2021; Andersson et al., 2018; Pigford et al., 2018). Despite calls to explore socio-techno-ecological system concepts (Ahlborg et al., 2019), this broader structural scope has not yet gained traction in the sustainability transitions literature. However, different variants of socio-techno-ecological systems are increasingly explored by scholars in adjacent fields that focus on risks and vulnerabilities (Chang et al., 2021; Gulsrud et al., 2018; Hellin et al., 2021), resilience (Andersson et al., 2021d; Chang et al., 2020; Krueger et al., 2022; Muñoz-Erickson et al., 2021), ecosystem services (Andersson et al., 2021c), ecological justice (Pineda-Pinto et al., 2021) and nature-based solutions (McPhearson et al., 2022) in urban contexts.

Based on this, we make a third proposition that clarifies the structural scope of TISs:

Proposition 3. *The structure of a TIS, as well as the associated production-consumption system, is social and technical, and may also include ecological elements.*

Finally, while we acknowledge that one can see a TIS as something that exists "out there", our propositions mainly concern an analytically constructed system model of change. In other words, the TIS framework should be understood in epistemological rather than ontological terms.

5.3. A preliminary guide to boundary setting in TIS case studies

When applying the TIS framework in empirical research, there is a need to establish the scope of a particular case study and delineate the system in focus in ways that are not given by the generic model discussed in the previous section. A necessary first step is to specify the system function by describing the technology in focus. While this can be done at different scales and levels of detail, it is key that analysts provide a clear delineation of the means and ends that are included. This is where understanding technology as a production-consumption system is useful, since the latter can be stringently defined by specifying a focal product (good or service) as well as a bundle of up- and downstream value chains in which this product is, or potentially could be, produced and consumed (Andersson, 2020; Sandén and Hillman, 2011).[17] Although this is much in line with the foundational literature, which made clear that specifications of TISs should include not only a focal product (or knowledge field), but also the breadth of included applications (Bergek et al., 2008a; Markard and Truffer, 2008), it is a worthwhile reminder given the often ambiguous technology definitions offered in more recent TIS studies.

A production-consumption system subject to a TIS study also has spatial boundaries. However, even if the production-consumption system is delimited to a specific region, the TIS does not have to have the same spatial scope. Spatial TIS boundaries (as with the production-consumption system in focus) can be set a priori to a specific region or be found through empirical observation (i.e. by following a network of actors where it leads). The merits of the latter approach have been thoroughly demonstrated in literature that engages with the geography of transitions (Binz et al., 2014; Coenen, 2015; Coenen et al., 2012; Hansen and Coenen, 2015) and were also raised in the foundational TIS literature (Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008). In particular, scholars have shown that there are often decisive couplings and interactions across regions and jurisdictions (Binz et al., 2014; Binz and Truffer,

[13] In mathematical, and systems dynamics terms, the TIS and its 'functions' can thus in principle (but perhaps not in practice) be understood as a set of linked differential equations describing how a multi-dimensional production-consumption system changes as a function of the structures of the system itself and exogenous factors, both in the form of factors in a surrounding context and in the form of actor agency (causation formed in processes at lower system levels).

[14] See Svensson and Nikoleris (2018) for a similar argument in relation to the multi-level perspective.

[15] Following the literature on socio-techno-ecological systems in other adjacent fields (c.f. Ahlborg et al., 2019), we use the term 'ecological elements' to refer broadly to biological and geophysical factors associated with the natural environment.

[16] Indeed, our view is similar to actor-network theory (Latour and Woolgar, 1979) in that it acknowledges that both humanly designed and naturally evolved material structures influence the outcomes of change processes. However, we refrain from discussing if this should be referred to as 'agency' or whether this concept should be reserved for human actors.

[17] More specifically, one needs to define both the complementary and alternative value chains that defines and delimits the focal production-consumption system (Sandén and Hillman, 2011).

2017; Gosens et al., 2017, 2015), which means that studies based on pre-conceived spatial boundaries may fail to identify important innovation dynamics.

A similar argument can be made about the temporal scope of a TIS study, which can also be set a priori or found through empirical observation in both retrospective and prospective studies. Here as well, a pre-conceived focus on a specific time period may conceal important innovation dynamics.

Nevertheless, most TIS studies rely on some system boundaries set a priori. Given the omnipresent limitations of time and resources, analysts must often completely disregard some activities in distant locations and deep historical roots. What matters is that such spatial and temporal limitations in the scope of a case study are explicitly stated and critically reevaluated as new information is revealed. This also highlights the important distinction between analytical system boundaries set a priori and empirical system boundaries discovered within that analytical space (Andersson et al., 2021b).

5.4. *Implications and future research*

While the discussion has thus far offered three propositions that may partly resolve ambiguities in the TIS concept, as well as some guidance to boundary-setting in empirical case studies, further scientific dialog is needed to increase clarity and rigor in the literature. More specifically, we believe that it would be worthwhile for the TIS community to advance towards a shared system model. This would not only benefit the growing strand of TIS research that develops formal computer models to simulate technological change (Holtz et al., 2015; Mirzadeh Phirouzabadi et al., 2022; Walrave and Raven, 2016), but also, and perhaps more importantly, contribute to identifying logical gaps and further improve the TIS framework conceptually. In turn, this may revitalize the literature and attract a new generation of scholars, students and practitioners to developing and using the TIS framework.

A more comprehensive system model building on the propositions in this paper requires development in several directions. For example, and as noted above, there is a need to develop a deductive theoretical basis for ‘functions’ based on how a TIS develops and shapes an associated production-consumption system. This may result in modifications to the ‘functions’ typologies commonly used by TIS scholars, or simply serve as a theoretical validation that would increase the rigor of functional analysis (see Andersson (2020) for recent work in this direction). It could also involve efforts to develop alternative approaches to analyzing ‘functions’, with a view to account for their role in not only developing, but also shaping, or even dismantling, technology (Kivimaa and Kern, 2016). Such increased attention to the directionality of technological innovation processes (Andersson et al., 2021b; Weber and Rohracher, 2012) may in turn contribute to reducing possible biases towards, for example, technology-push policy recommendations.

Conceptual development is also needed to establish representations and categorizations that enable the inclusion of ecological elements in models of TISs and associated production-consumption systems. Notably, such efforts may draw on socio-techno-ecological systems frameworks and other ways to account for nature in other fields (Markolf et al., 2018; Selin and Selin, 2022; Sorge et al., 2022; Vogel et al., 2021).

In addition, it is necessary to test and validate these theoretical ideas through empirical research in different geographical and sectoral contexts. An important empirical question is to find the appropriate level of specificity in representations and categorizations (e.g. regarding structural elements). As discussed above, some theoretical ideas should be integrated with the generic system model, while others must be specified in each case study. And it is only through empirical research that the right balance between generality and specificity can be found.

Lastly, the ideas presented in this paper could also shine light on possible ambiguities in other systems approaches to innovation and technological change. In particular, we would encourage scholars that engage with novel innovation systems approaches, focusing on broadly defined missions (Hekkert et al., 2020; Sonnier and Grit, 2022) and more specific problems (Ghazinoory et al., 2020), to strive for clarity and rigor with respect to the underlying system model in order to avoid some of the issues raised in this paper.

6. Concluding remarks

This paper set out to review how the functional and structural scope of TISs are understood in the literature. We identified ambiguities and contradictions that hinder cumulative knowledge development and conceptual advancements. We also took steps towards more clarity and rigor by proposing: that the overarching function of a TIS is to develop and shape a specific technology; that this technology can be understood as a production-consumption system; and, that the structure of a TIS is social and technical, and may also include ecological elements. In addition, we offered some guidance to boundary-setting in empirical case studies. We hope that the observations and propositions made in this paper will inspire the TIS community to advance towards a shared system model of technological change.

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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