Overcoming transformational failures through policy mixes in the dynamics of technological innovation systems

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Rob Raven, Copernicus Institute, Utrecht University, r.p.j.m.raven@uu.nl
Bob Walrave, ITEM, Eindhoven University of Technology, b.walrave@tue.nl

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ABSTRACT
The need for challenge-led innovation policies to address grand societal challenges is increasingly recognised at various policy levels. A key-line of research has emerged on the role of systemic failures in the development of Technological Innovation Systems. Recent work, introducing the notion of 'transformational failures', has combined this rationale with the work on multi-level approaches to sustainability transitions. This literature, so far, has failed to explore how different kinds of policies can overcome such transformational failures. This paper uses a system dynamics model to explore relations between transformational failures and policy interventions, and study the ways in which they influence the development of TIS in various transitions contexts. One conclusion is that, in particular in the case where TIS is in a competitive relation with the regime, overcoming reflexivity failures are critically important.

1. Introduction

The need for challenge-led innovation policies to address grand societal challenges is increasingly recognised at various policy levels (Steward, 2012; Coenen et al., 2015). The argument is that 'wicked problems', such as climate change, require new forms of innovation policies that move beyond a narrow 'technology-driven' and 'supply-side' orientation. In challenge-led innovation policies, innovation is understood as a systemic and evolutionary process in which technologies, markets, user preferences, policies, infrastructures, knowledge paradigms and culture co-evolve as a system in the context of major societal challenges that demand a fundamental restructuring of existing socio-technical systems. In particular, the literature on 'sustainability transitions' (Markard et al., 2012) has been explicitly conceptualising the dynamics of such transformations through frameworks such as technological innovation systems (TIS) (Bergek et al., 2008; Hekkert et al. 2007; Markard and Truffer, 2008) and the multi-level perspective (MLP) (Rip and Kemp, 1998; Geels, 2002).

Alongside conceptual development scholars have engaged in thinking through the implications and rationales for policy intervention for the development of sustainable innovation. On this topic, a key line of research has emerged, which moves beyond the narrow notion of 'market failures' and develops a more encompassing 'systemic failures' framework that takes into account the evolutionary and systemic nature of innovations (Smith et al., 2004; Woolthuis et al., 2005; Wieczorek and Hekkert, 2012; Mierlo et al., 2010). Another line of research builds upon the multi-level perspective to develop reflexive governance approaches (Voss et al., 2006) such as strategic niche management (Kemp et al., 1998; Schot et al., 2008; Smith and Raven, 2012) and transition management (Rotmans et

al., 2001; Loorbach, 2010). Recently Weber and Rohracher (2012) attempted to combine these lines of reasoning into an elaborated framework on 'transformational failures'—claiming that this framework can build upon the widely accepted notion of 'failures' as a legitimate argument for policy intervention, whilst at the same time enabling a more reflexive approach building upon multi-level perspective reasoning.

Whilst this 'transformational failures' framework developed by Weber and Rohracher (2012) is useful for developing a new *legitimation* for innovation policy, it has so far not yet resulted in more specific proposals for policy *interventions* that may overcome transformational failures. Moreover, recent scholarship has started to argue that such policy interventions should be understand in terms of 'mixes' or 'portfolios', which in TIS terms implies a particular combination of interventions that target multiple TIS functions simultaneously (Rogge and Reichardt, 2016; Kivima and Kern, 2016). This paper aims to make precisely this contribution by proposing particular links between the 'failures' identified by Weber and Rohracher (2012) and the functions in the technological innovation systems framework. More specifically, this paper will use a recently developed system dynamics model on the dynamics of technological innovation systems in various transition contexts (Walrave and Raven, 2016) to explore to what extent policy interventions inspired by Weber and Rohracher's transformational failures framework shape the dynamics of technological innovation systems. Hence, the research question for this paper is formulated as follows: *How do technological innovation systems respond to policy interventions directed to overcome transformational failures?*

The remainder of this paper is structured as follows. The next section provides the literature background and proposes a scheme for linking transformational failures to interventions in technological innovation systems in various transition contexts. Section 3 explains our approach, and in particular the system dynamics model, and the ways in which the different transformational interventions are operationalized. Section 4 presents the results and section 5 discusses and concludes.

2. Transformational interventions in TIS dynamics

The literature on technological innovation systems has substantially increased over the past years. What sets this literature aside from conventional innovation systems approaches is its explicit focus on 'dynamics' as a critical aspect of analytical inquire complementary to analysis of systemic structures. Foundational TIS papers, such as Hekkert et al. (2007) and Bergek et al. (2008), have developed useful analytical schemes to identify and assess the *functional* dynamics of TIS. Functions refer to a set of processes that an innovation system around a particular technology needs to perform in order to successfully develop over time. These functions are:

(1) entrepreneurial activities,
(2) knowledge development,
(3) knowledge diffusion,
(4) guidance of the search,
(5) market formation,
(6) mobilization of resources,
(7) creation of legitimacy.

Methodologically, the mapping and analysis of these functions effectively allows for diagnosing the performance of a particular technological innovation system. Conceptually, functional dynamics are argued to shape the structural dimensions of a TIS (Hillman and

Sandén, 2008). In case of structural system weaknesses (Jacobsson and Bergek, 2011), governance interventions in the functional dynamics of TIS can thus help to overcome such weaknesses.

The innovation systems literature was developed in response to a predominantly neo-classical linear thinking on innovation processes, and in particular in response to the narrow policy rationale around 'market failures', which followed from such linear thinking. In short, this market failure policy rationale acknowledged only two legitimate reasons for interventions in innovation processes (Jacobsson and Bergek, 2011): positive knowledge externalities (referring to the argument that firms tend to under-invest in research and development due to the risk of knowledge spillovers that may benefit other firms) and negative environmental externalities (referring to the argument that markets generally do not internalise environmental costs into prices). Systemic innovation scholars argued that such policy rationale is too narrow, because it does not consider the structural conditions and weaknesses that may hinder innovation, such as institutional, network or infrastructural weaknesses.

System innovation scholars started to develop additional rationales for policy interventions that go beyond a linear understanding of innovation, considering the systemic nature of innovation (Smith and Kuhlman, 2004). Woolthuis et al. (2005) proposed a framework around 'system failures', which distinguishes between infrastructural, institutional, interaction and capabilities failures. Wieczorek and Hekkert (2012) further developed this framework into an analytical scheme for proposing systemic instruments based on a functional and structural analysis of a TIS.

Recently, both innovation policy practitioners and scholars started to broaden again the rationale for policy interventions in innovation processes, based on insights emerging from multi-level analyses of transitions towards sustainability (Smith et al. 2010). The argument is that whilst the innovation system approach has extended our understanding on the range of variables that explain the successful development and diffusion of innovations, its *problem framing* is still focused on how so successfully support the development and diffusion of those innovations. What is still missing is a sophisticated understanding of the policy challenges around a problem framing that is concerned with how transitions in entire socio-technical systems towards sustainability come about, and the kind of 'failures' may hinder such a transition. As Weber and Rohracher (2012: 1042) argue: "*Additional types of failures come into play, due to the broader scope of transformative change as compared to innovation performance only, and due to the long-term and fundamental character of the transformation process in question… Conventional market and system failure arguments to legitimize policy interventions are useful and valid, but they are confined to addressing structural deficits in innovation systems, and do not give sufficient justice to the kinds of arguments from the multi-level perspective that have been identified as preventing processes of transformative change from occurring in a socially and politically desirable way*."

Arguably, there are at least two overarching issues that conventional 'failures' thinking fails to address. First, conventional (market and systems) failures thinking does not consider the complex governance challenges emerging from a situation in which multiple TIS co-exist that can address grand societal challenges. For instance, there are multiple innovation systems around technologies such as solar energy (ranging from decentralised to large-scale), on- and offshore wind energy, a range of bio-energy technologies, carbon capture and sequestration and demand side reduction. Market price dynamics alone may be

insufficient to select between these TIS from a broader societal perspective, as each of them shapes particular distributions of social benefits and risks (such as new geo-political risks, or environmental implications such as landscape changes). Second, conventional failures thinking fails to address governance challenges emerging from differentiated institutional positions (and associated power) of incumbent regime networks versus emergent TIS networks. In this respect, incumbents are bound to have more resources, such as financial, political and human resources, and use them to influence institutional frameworks such as policy frameworks for, let us say, energy transitions. For instance, without explicitly considering this imbalance in political power, it has been demonstrated that the policy frameworks put in place for transforming energy systems may in fact contribute to strengthening the position of existing systems rather than challenging them (Kemp et al., 2007). Put differently, whereas the system failures framework does address how to build up an emergent TIS, it does not address the discontinuation or destabilisation of existing regimes (Turnheim and Geels, 2012).

Both kinds of overarching governance challenges can be addressed through an extension of the failures framework to include a 'transformational' perspective. Indeed, Weber and Rohracher (2012) have started to conceptualise these challenges and complemented the previous rationales of 'market failures' and 'structural system failures' with the notion of 'transformational system failures' to consider such a broader transition perspective on innovation for sustainable development. They do so by explicitly combining the technological innovation systems approach with the multi-level perspective on sustainability transitions. Weber and Rohracher (2012) distinguish four types of 'transformational system failures'.

1. *Directionality* failures refer to the observation that in the context of grand societal challenges, there is a need to consider the direction of innovation in such a way that innovation contributes to those societal challenges. Technological innovation systems may fail to develop endogenously into the desired direction (because those directionality requirements emerge outside of the TIS, e.g. in policy arenas or through societal debates), which legitimises additional policy intervention.
2. *Demand articulation* failures refer to the observation that in the context of grand societal challenges, markets for new technologies may not exist 'out there', resulting in a lack of articulation of what markets requirements are or what user preferences are, and therefore 'a deficit in anticipating and learning about user needs'.
3. *Policy coordination* failures refer to the observation that in the context of grand societal challenges, policies and public institutions may need to transform in response to those challenges as well as develop innovations to address those challenges. Policy coordination failures can occur between different policy levels (vertical policy coordination failures) or between different sectors (horizontal policy coordination failures).
4. *Reflexivity* failures refer to the observation that in the context of grand societal challenges, there is a need for continuous monitoring of TIS development with respect to the progress towards the broader transformation goals and the development of adaptation strategies.

We believe that this typology of transformational failures provides a useful starting point for legitimizing interventions in the dynamics of TIS in the context of grand societal

challenges. Weber and Rohracher (2012), however, are somewhat less clear on how this typology translates into interventions in an emerging TIS, and how such interventions can shape the dynamics of an emerging TIS.

In this paper, we adopt a formal system dynamics model that was previously developed to explore the dynamics of TIS in various transition contexts. This model is discussed in more details elsewhere (Walrave and Raven, 2016). The model is based on a combination of the literature on TIS, and in particular the concept of 'motors of innovation' (Suurs, 2009) with the literature on socio-technical transition pathways (Geels and Schot, 2007). Motors of innovation refer to interaction patterns between different TIS functions. Suurs (2009) distinguishes four motors on the basis of extensive empirical case study research on emerging innovation systems:

The *'science and technology push motor'* refers to patterns in innovation systems in which formal, scientific knowledge development and diffusion are central, supported by R&D programmes and policy support. This knowledge production and diffusion shapes initial experimental projects and other entrepreneurial activities, which may increase further financial and political support when outcomes confirm initial expectations, or, in turn, may reduce support when the results of these projects are perceived as negative. The key TIS functions in this motor are 'knowledge development', 'knowledge diffusion', 'guidance of the search' and 'resource mobilization'.

The *'entrepreneurial motor'* refers to patterns in innovation systems in which core dynamics are constituted by an increasing number of firms and entrepreneurs becoming active in the innovation system, which increases legitimacy in the eyes of external funders such as governments. There is also ad-hoc advocacy for further external resource provision, for instance by firms aiming for temporary financial support to reduce risks when investing in uncertain projects. Through precarious commercial activities in niche markets, some initial financial resources are also generated internally in the innovation system. These then feed back into knowledge development, when for instance feasibility studies or reviews of demonstration projects are published. Hence, learning dynamics constituting this motor are broadening from learning-by-searching to include learning-by-doing. The key-functions in this motor are similar to those in the 'science and technology push motor', but 'entrepreneurial activities' and 'creation of legitimacy' are also strongly present.

The *'system-building motor'* is a pattern in innovation system dynamics that is constituted by increasing organisation of actors in networks, infrastructural developments and attempts at institutional reconfigurations. The type of actors supporting the innovation system broadens and starts to attract wider societal support (e.g., Bergek et al., 2008b), for instance through the establishment of user communities, or the institutionalisation of policy ambitions in reconfigured regulatory rules, or the construction of physical infrastructures such as a wide-spread network of charging stations for electric vehicles. The system-building motor is socially and politically a particular challenging phase in innovation system developments, as the required resources will increase substantially compared to the 'science and technology push' and 'entrepreneurial' motors, whilst at the same time internally generated resources through market sales are still limited. Organising for sustained advocacy over longer time frames is, therefore, considered a key process in this motor. All functions are important in this motor, but the 'market formation' function is most critical (Suurs, 2009: 219).

When innovation system actors successfully navigate this 'valley of death', an innovation system is argued to be constituted by a *'market motor'*. This refers to a pattern

in an innovation system that is internally resourced through substantial market demand, which is sufficient for maintaining all necessary processes in the innovation system. Advocacy for the innovation system has institutionalised into hidden patterns of social and political support, and legitimacy of an innovation system is no longer explicitly questioned. In terms of functions, all functions are important in this motor, but 'creation of legitimacy' is less critical (Suurs, 2009: 233).

In our model, we contextualise emerging innovation systems with the notion of socio-technical transition pathways (Geels and Schot, 2007). The notions of regime and landscape, as developed in the context of the multi-level perspective, provide fruitful avenues for exploring this interplay between innovation system and context (Markard and Truffer, 2008; Bergek et al., 2015).

In short, Geels and Schot (2007) distinguish between four transition pathways, which can be conceptualised as four different contexts for an emerging TIS. A '*transformation pathway*' refers to a context in which (1) landscape pressures occur at a moment when a technological innovation system has not yet developed substantially; and (2) regime resistance is large because regime-actors respond to these pressures by increasing their innovative efforts on the dominant socio-technical design, and only slowly and hesitantly look for innovations beyond regime boundaries. A '*de-alignment and re-alignment pathway*' refers to a context in which (1) landscape pressures also occur at a moment when a technological innovation system has not yet developed substantially; but (2) regime-actors lose faith in the existing socio-technical regime and search pro-actively for alternatives, that is, regime resistance is relatively small. A '*technological substitution' pathway'* refers to a context in which (1) landscape pressures occur at a moment when a technological innovation system has benefited from previous substantial support and development efforts; and (2) regime-actors continue to support the incumbent socio-technical configuration through innovative efforts. Finally, a '*reconfiguration pathway'* refers to a context in which (1) landscape pressures also occurs at a moment when a technological innovation system is already developed substantially; and (2) regime-actors start adapting (elements of) this innovation system into the existing socio-technical configuration, which implies a relatively low regime resistance.

The following section will elaborate in more detail the modelling approach of the paper and the choices regarding our experimental setup.

3. Modelling transformational system failures

In order to study how technological innovation systems respond to policy interventions, directed to overcome transformational failures, we adopt a system dynamics model (Walrave and Raven, 2016). System dynamics modelling is especially suitable for investigating dynamically complex phenomenon, like technological innovation systems, as it allows for studying feedback, delays, and other non-linear effects; characteristics that are commonly observed in studies on TIS. Furthermore, the method also allows for experimentation by means of the so-called *if-then* simulation experiments, enabling researchers to conduct experiments that are otherwise difficult to test in empirical settings—such is the case here.

As explained, the model combines the concept of 'motors of innovation' (Suurs, 2009) with the literature on socio-technical transition pathways (Geels and Schot, 2007). As the model is explained elsewhere in full detail (see Walrave and Raven, 2016), we only provide a summary of the main feedback loops. Figure 1 details the model.

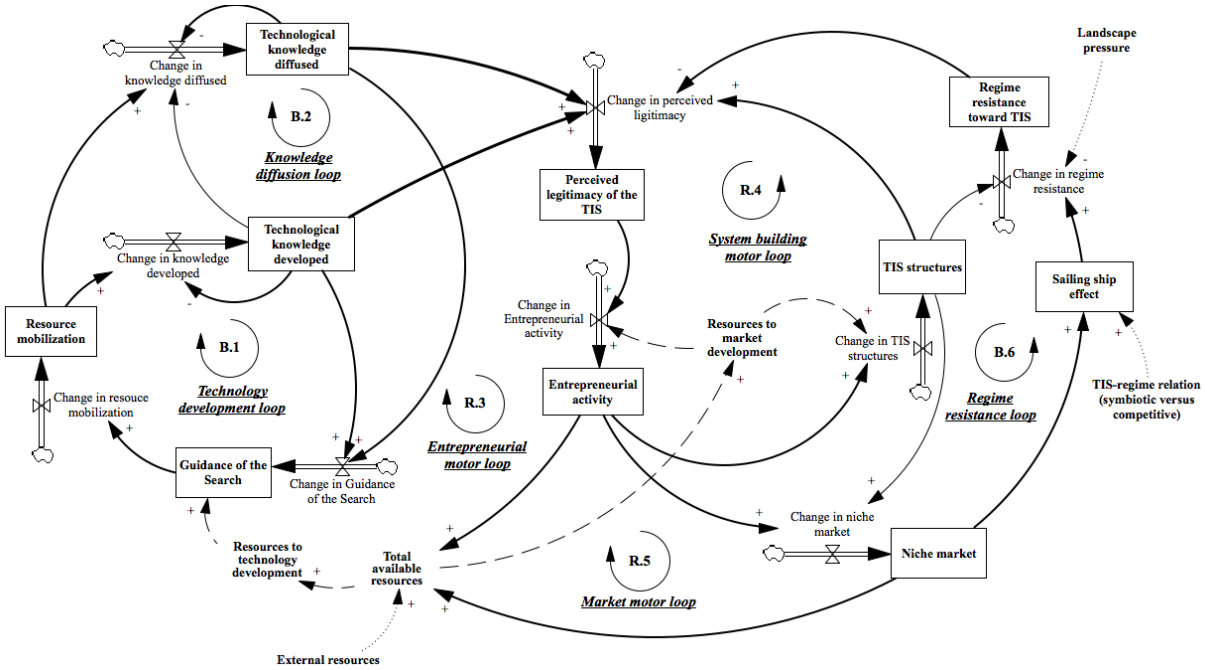


Fig. 1. Stylized overview of the model (adapted from Walrave and Raven, 2016).

The model consists of six feedback loops, reflecting the motors of innovation (Suurs, 2009), which subsequently include the seven functions as described by Hekkert et al. (2007). More specifically, technology development is captured by two balancing feedback loops, the 'Technology development loop' (i.e, B.1 in Fig. 1) and 'Knowledge diffusion loop' (B.2), which combined denote the *'science and technology push motor'*. The model also captures self-reinforcing market dynamics by including the 'Entrepreneurial motor' (loop R.3), the 'System building motor' (loop R.4), and the 'Market motor' (loop R.5). Furthermore, the model incorporates the notion of different transition pathways developed by Geels and Schot (2007) by recognizing the 'Regime resistance loop' (B.6), which counteracts the reinforcing market-side dynamics by acting as a potentially strong TIS opposing force.

Note that the model is developed to replicate only early stage TIS growth (and potential decline) (Walrave and Raven, 2016)—and this limitation is carried over to this research. Nevertheless, the model is very suitable to study the focal research question as it (a) captures TIS dynamics through specific inclusion of TIS functions and associated causal relations (motors of innovation incl. delays and non-linearity's); (b) explicitly combines the TIS framework with the multi-level perspective; *and* (c) is specially attuned to grand societal challenges and wicked problems—building on generic causal relations identified in the literature, in the context of TIS emergence. As such, coupling the transformational system failures to this formal model allows for experimenting with policy interventions designed to target specific transformational failures and explore to what extent policy interventions inspired by transformational failures shape the dynamics of technological innovation systems. However, the current model is not able to address governance challenges for situations in which multiple TIS co-exist. This will be discussed in the final section.

We assume the following relations between transformational failures and particular policy interventions. In each case, we distinguish between a 'primary' function that is targeted by a particular policy intervention, and a 'supportive' function. The core function is

considered to be key to overcoming a certain transformation failure, whilst the secondary function is considered to more indirectly related to overcoming that failure.

A directionality failure refers to a lack of consideration concerning the direction of the innovation so that it contributes meaningfully to the grand societal challenge at hand. Such situation causes for, among others, insufficient regulations or standards and lack of targeted research funding. As such, directionally failures are overcome by development of shared vision concerning the goal and direction of the development (Weber and Rohracher, 2012). This resonates with the development of the TIS *internal* function 'Guidance of the search' ('Science and technology push motor' in Fig. 1), which denotes "those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users" (Hekkert et al., 2007: 423) and "represents the selection processes necessary to facilitate a convergence in development" (Suurs, 2009: 268). Furthermore, overcoming this failure also requires translation and intermediation of guiding orientations at the TIS *external* level (Weber and Rohracher, 2012)—at the TIS-regime interaction level. Therefore, overcoming a directionality failure requires mitigation of the regime resistance toward the TIS, in order to gain support for the future of the TIS from powerful regime incumbents. Therefore, directionality failures can seemingly be overcome by *primarily* supporting the 'Guidance of the search' function in combination with *supportive* efforts to decrease regime resistance towards TIS.

A demand articulation failure concerns a lack of articulation of markets requirements and user preferences. A primary reason underlying this failure concerns the lack of spaces to anticipate and learn about user needs, required for (future) innovation diffusion activities (Weber and Rohracher, 2012). As such, counteracting this failure requires joint learning processes that involve producers and users. Concepts and ideas such as living labs and strategic niche management might be employed to achieve this goal. This corresponds to the development of the TIS function 'market formation' ('Niche market', part of the 'Market motor loop' in Fig. 1), which entails, among others, the creation of protected spaces (e.g., temporary niche markets or favourable tax regime) for new technologies (Hekkert et al., 2007). In this respect, new technologies are oftentimes not able to outperform established solutions, and require such a protected space to be able to grow increasingly competitive (Kemp et al., 1998). That is, within such protected environments "actors can learn about the new technology and expectation can be developed" (Hekkert et al., 2007: 242), without being subjected to a strong selection environment. In the context of transformational failures, this also implies that regime resistance toward the TIS should be managed. As such, this suggests that demand articulation failures may be best overcome by *primarily* supporting the TIS function 'market formation' in combination with *supportive* attempts to lower the regime resistance towards TIS.

A policy coordination failure implies a lack of policies and public institutions required to transform and develop innovations to address a specific grand societal challenge. As explained earlier, this may concern multi-level (vertical *and* horizontal) policy coordination failure and, as such, implies a lack of alignment between, for instance, public policy and private sector institutions (Weber and Rohracher, 2012). Such structural elements are partly captured, at the vertical level, by 'TIS structures' (see Fig. 1). In this respect, TIS structures capture the relationship between the different TIS functions and the structural dimensions of the TIS (Walrave and Raven, 2016). Furthermore, such alignment also needs to be present at the TIS-regime interaction level, which reflects (a part) of the horizontal level. Indeed, this failure refers to the "need for coherent policy impulses from different policy areas in order

to make sure that […] the necessary goal-oriented transformative changes for tackling major societal challenges can be achieved" (Weber and Rohracher, 2012: 1043). Therefore, policy coordination failures can potentially be mitigated by *primarily* supporting 'TIS structures' in combination with a *supportive* decrease in regime resistance towards TIS.

Finally, a reflexivity failure implies insufficient monitoring, anticipation and involvement of actors in TIS development, with respect to the progress towards the broader transformation goals and the development of adaptation strategies. This likely results in deterioration of the TIS-regime relationship as reflexivity is closely linked to the provision of interaction platforms—which limits higher order learning where "actors reflect on the conditions and engage in the transformation of the very systems in which they operate" (Weber and Rohracher, 2012: 1044). The model, as denoted in Fig. 1, captures such state of the TIS-regime relationship through 'Regime resistance towards TIS', which is part of the 'Regime resistance loop' (loop B.6). Furthermore, reflexivity draws on an evidence-based approach that is needed to legitimize policy interventions and, as such, bring about legitimacy for the TIS.[1] Therefore, we argue that overcoming reflexivity failures require *primarily* a reduction of regime resistance towards TIS (e.g., through new social arrangements with key stakeholder groups such as 'hybrid forums') in combination with *supporting* the TIS function 'Creation of legitimacy'.

Concluding, in this paper we assume the following links between the failures framework by Weber and Rohracher (2012) and TIS functions in the following way:

1. *Directionality failures can be overcome by providing support for the function 'guidance of the search' and the reduction for regime resistance towards TIS.*
2. *Demand articulation failures can be overcome by providing support for the function 'market formation' and reducing regime resistance towards TIS.*
3. *Policy coordination failures can be overcome by providing support for 'TIS structures' and reducing regime resistance towards TIS.*
4. *Reflexivity failures can be overcome by reducing regime resistance towards TIS and by providing support for the function 'legitimacy'.*

3.1 Experimental setup

Our experiments set out with the 'hybrid' resourcing condition (see Walrave and Raven, 2016). This specific resourcing condition implies that a TIS can initially draw substantially on technology-oriented resources, while in later development phases it can draw on significant market-oriented resources. Resources are available over a period of 15 years. While this setup was found to be most efficient for early stage TIS development, this resourcing condition is by no means a guarantee for success as many experiments still failed (Walrave and Raven, 2016)—potentially due to (a) transformational system failure(s).

As such, following upon this initial resource provision of 15 years, we explore how a *second* round of resource provisions shapes the dynamics of a TIS. We assume that the resources equal 50% of the initial resources, distributed over a period of 5 years. The additional resources, following the four kinds of transformational system failures, are provided at the moment that the TIS exhibits structural decline, which we assume is

[1] While not supported in our model, a portfolio approach might also be employed to reach this goal.

indicated by a sustained negative trend in niche market growth.[2] Table 1 denotes the relation between the different transformational system failures and TIS functions involved *and* the distribution of the additional resources over the different processes that are targeted by the different policy interventions. We initially assume in each case that 80% of the resources are provided to the primary function related to a particular transformational failure and the remaining 20% to the supportive function.

Note that we also ran sensitivity tests with respect to the chosen distribution (i.e., 80/20). We found that the results are robust to variations in the resource distributions over primary and supportive functions. The sensitivity analyses are included in the model appendix.

Table 1: Transformation system failures in relation policy intervention

	Transformational system failure type	**Primary function involved in policy intervention**	**Supportive function involved in policy intervention**
	Additional resource distribution	**80%**	**20%**
1	Directionality failure	'Guidance of the search'	'Regime resistance toward TIS'
2	Demand articulation failure	'Market formation'	'Regime resistance toward TIS'
3	Policy coordination failure	'TIS Structures'	'Regime resistance toward TIS'
4	Reflexivity failure	'Regime resistance toward TIS'	'Perceived legitimacy of the TIS'

The original model by Walrave and Raven (2016) is designed to reflect four different transition contexts (the transformation pathway, the de-alignment and re-alignment pathway, the technological substitution pathway, and the reconfiguration pathway) (Geels and Schot, 2007). Under each pathway, a TIS is subjected to different resourcing conditions. The results by Walrave and Raven (2016) indicated that the dynamics of TIS vary substantially depending on the different pathway contexts. In particular, more symbiotic regime-TIS relationships and early stage TIS development (i.e., before the occurrence of a landscape event) are associated with a higher likelihood that a self-sustainable TIS emerges. In this paper, we follow Walrave and Raven (2016) and also conduct our experiments within these four different pathways to investigate the influence of the proposed policy interventions in different contexts. Therefore, 16 experiments are devised: four different policy interventions that are hypothesized to counteract transformational systems failures in four different contextual situations.[3]

[2] More specifically, the second round of investment is triggered by the 3-year moving average of 'Change in niche market' (see Fig. 1). We assume that a negative value of this variable effectively indicates a structural decline in niche market activities, signposting TIS failure, which triggers the release of additional resources, directed to prevent a transformational system failure. See the model appendix, available directly from the authors, for more details.

[3] Note that a detailed model appendix detailing all amendments to the original model to facilitate the proposed experiments, is available from the authors following acceptance of this manuscript.

4. Results

Figure 2, 3, 4, and 5 depict the results of the model runs; for de-alignment and re-alignment, reconfiguration, transformation, and technological substitution respectively. These figures denote the results for 'Niche market' (see Fig. 1), and, as such, these dynamics denote the viability of the TIS. We also included a reference run per contextual situation. This specific run was *not* subject to any secondary intervention and, as such, serves as the point of reference. Note that the de-alignment and re-alignment and reconfiguration context are both characterized by a favourable TIS-regime relationship (i.e., initial low regime resistance toward TIS). As such, both reference runs (in Fig. 2 and 3) already resulted in a sustainable TIS as the result of the initial resource provisions (also see Walrave and Raven, 2016).

First, overall, the results indicate that all policy interventions to overcome transformational system failures, initiated around t = 270, result in a larger niche market in all four transition pathway situations. In this respect, additional support to overcome transformation system failures, through key investments in interlinked TIS functions, seem to be a fruitful way to stimulate TIS development. These results also emphasize the importance of moving beyond assessment of individual functions, towards a system's view on matters, including a policy mix or portfolio of interventions targeting multiple TIS functions (Weber and Rohracher, 2012; Walrave and Raven, 2016).

Second, the different policy interventions, however, have varying effects on niche market growth. More specifically, from the four interventions, the one designed to target reflexivity failures results in the largest niche market growth—independent of contextual situation. Furthermore, a reflexivity failure informed policy intervention is the only one effective in the context of an unfavourable TIS-regime relationship (see Fig. 4 and Fig. 5). As such, our findings suggest that when faced with grand societal challenges, focusing on policy interventions that shape reflexive learning processes within TIS and between TIS and regime is very important. Such interventions support actors to reflect and engage in the transformation of the systems in which they operate, which subsequently limits the strong balancing effect of the 'regime resistance loop' (see Fig. 1, loop B.6), allowing for the market dynamics to emerge and grow increasingly strong. Of course, this does not imply that the other interventions are not important, but our results indicate that preventing a reflexivity failure, and therefore simulating the *self-reinforcing* market side of the TIS, is critical for successful TIS development.

Third, notably policy interventions designed to act against demand articulation failures have, on the short term, the largest effect on niche market growth in case of a symbiotic TIS-regime relationship, that is, in 'de-alignment and re-alignment' and in 'reconfiguration' contexts (see Fig. 2 and Fig. 3). As such, this type of policy might be especially effective in those situations where quick recognition (and market development) of the TIS is important. However, we note that this short-term positive effect is not effective in the context of an unfavourable TIS-regime relationship, that is, 'transformation' and 'technological substitution' contexts. The reason for this is that policy targeting demand articulation failure is arguably not likely to overcome an unfavourable TIS-regime relationship fast enough, as it often takes too much time to lure regime actors around the hostile TIS-regime relationship on the basis of relatively small niche markets alone. As such, once policy support ends, the TIS declines again (as illustrated by Fig. 4 and Fig. 5).

Fourth, the results suggest that in case of 'de-alignment and re-alignment' and 'reconfiguration' contexts there are different policy interventions that policy makers can use

for stimulating TIS, whilst achieving more or less similar results. Indeed, policy intervention against directionality failure and policy coordination failure show very similar dynamics in case of a competitive TIS-regime relationship. In case of policy against the directionality failure, the results show that although the positive effect is delayed, through stimulating the Guidance of the Search, almost the same positive self-reinforcing market dynamics can be achieved as was the case for policy intervention against demand articulation failure. The same can be said about policy against coordination failures (although the effects of this intervention are even more delayed), but here the positive effect is the result of strategic investment in TIS structures (rather than in TIS functions). Hence, our results suggest that supporting the Guidance of the Search, market formation or TIS structures have more or less the same result for niche market growth—albeit with varying delays.

Fig. 2. Context: De-alignment and Re-alignment. Results for 'Niche market'.

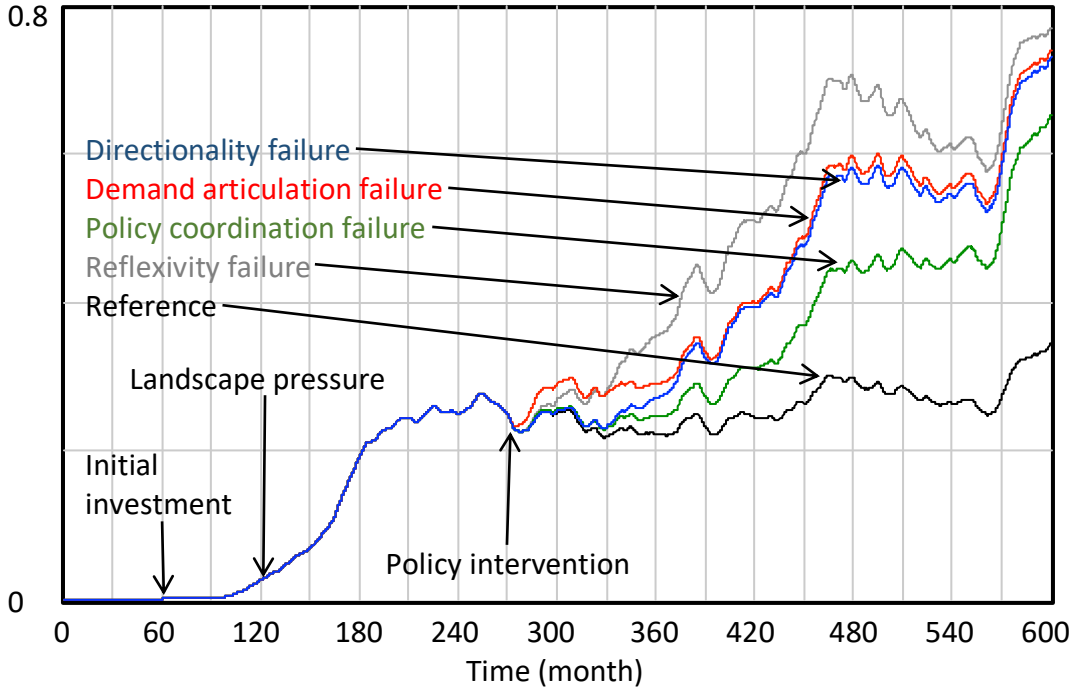


Fig. 3. Context: Reconfiguration. Results for 'Niche market'.

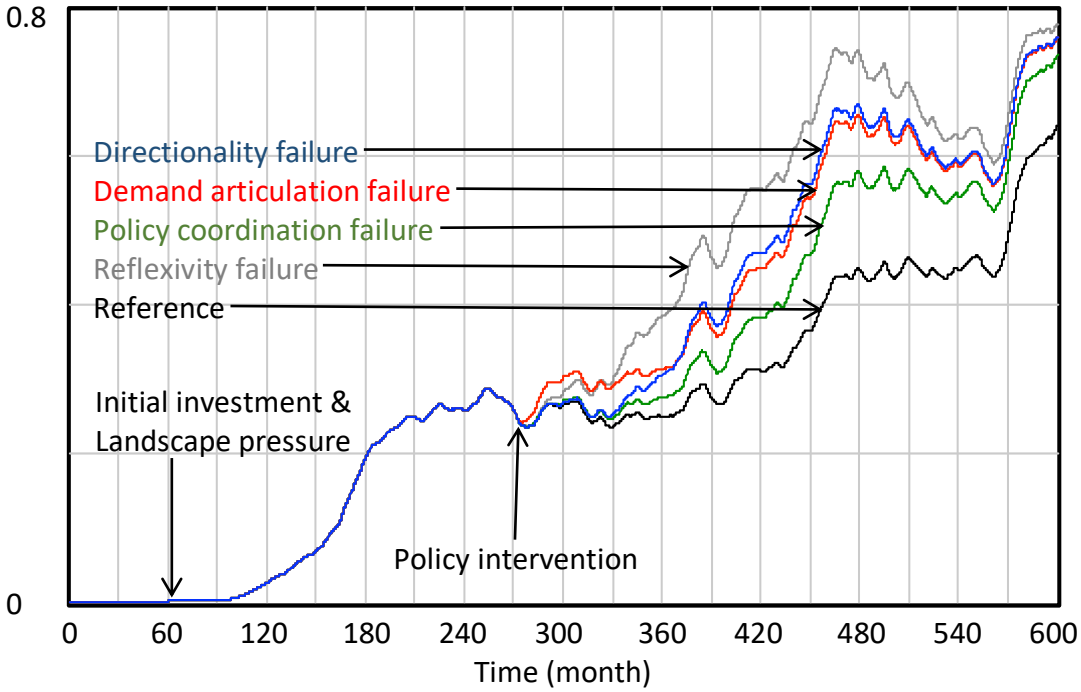


Fig. 4. Context: Transformation. Results for 'Niche market'.

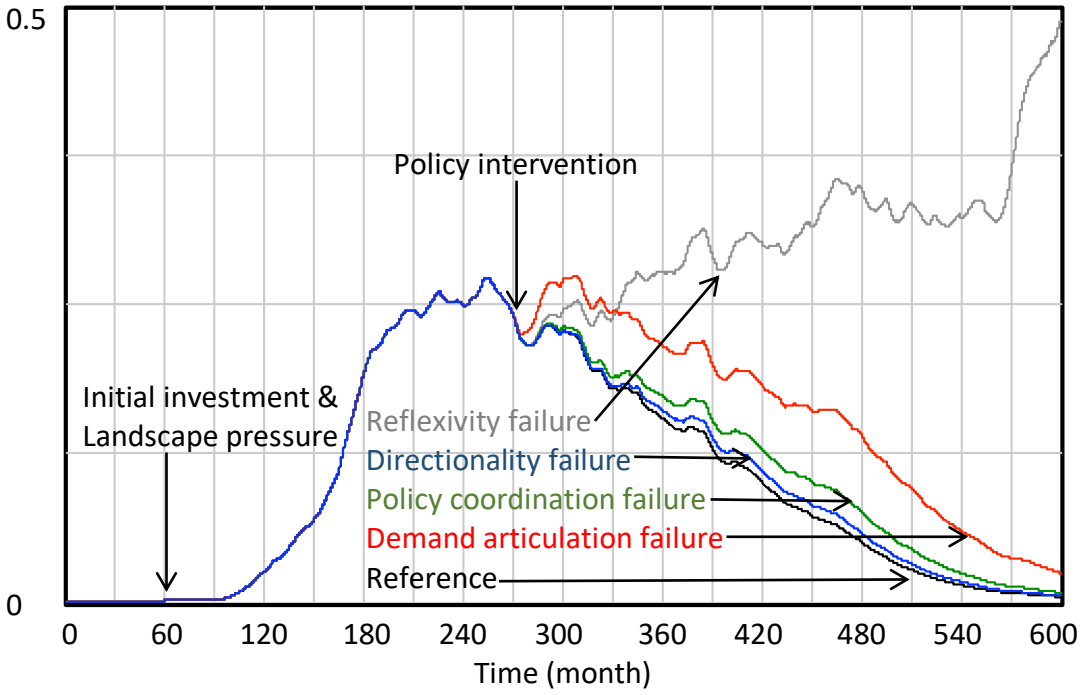
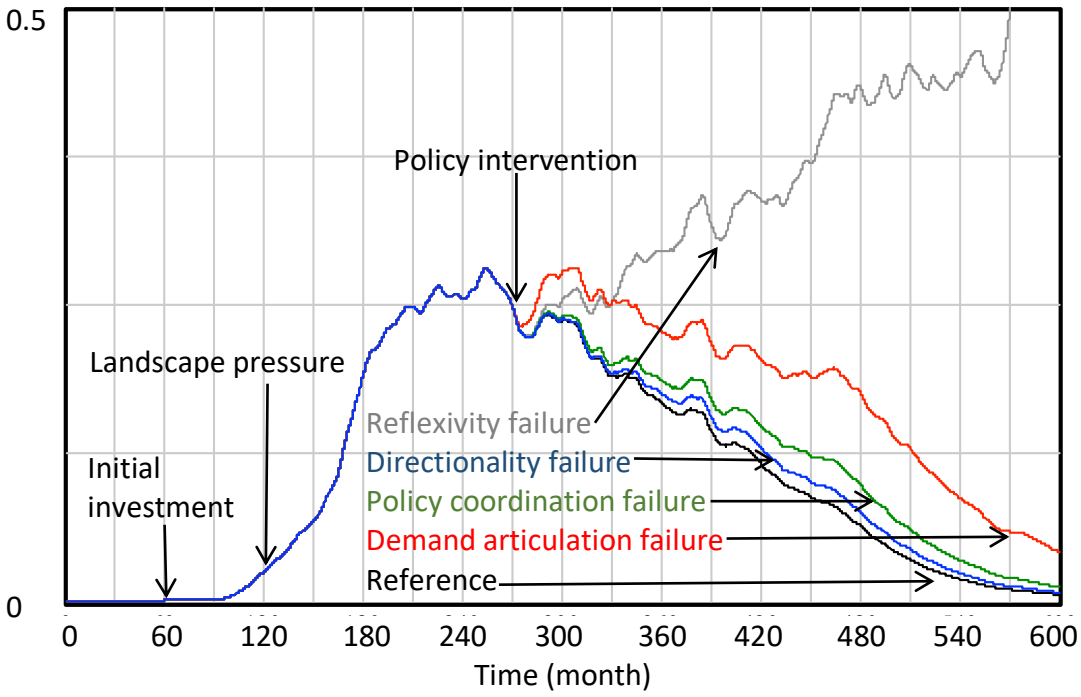


Fig. 5. Context: Technological substitution. Results for 'Niche market'.



5. Discussion

The presented results provide a sense of what the critical relationships are between transformational failures on the one hand, and implications of policy interventions on the other hand. As with any model (or any methodological approach for that matter), there are certain limitations and assumptions that deserve further discussion.

First, a key aspect of the model runs is that they assumed certain relationships between failures, policy interventions and functions (see Table 1). Whilst these relationships were built upon our reading of the failure descriptions in Weber and Rohracher (2012), we note that further empirical work, for instance through case study research, is necessary to support these assumed relations. Whilst there is some pioneering work (cf. Reichardt et al., 2016), we so far have little evidence on how to link observed transformational failures to specific interventions in functional dynamics. Hence, future empirical research is necessary to test our modelling assumptions. Alternatively, the current model could also be used to systematically review all possible combinations of interventions at the moment that structural decline sets in, in order to identify from the bottom-up, which combinations of interventions generate the most positive result.

Second, we note that acting upon observed transformational failures of course requires a way of knowing these failures are happening in the first place. This is not straightforward. In conventional TIS analysis, diagnostic questions are 'asked' to a particular case in order to assess which functions perform well and which perform not very well, for instance, through interviews with key informants and/or through event history analysis using grey material (Bergek et al., 2008; Suurs, 2009). Our analysis as well as the literature on transformational failures and policy mixes, however suggests that next to identifying limitations in dynamics of individual functions, it becomes very important to understand the dynamics in interactions between functions, and the ways in which different policy mixes can influence those dynamics. This may need different analytical and methodological tools, in which formal models like the one in this paper may prove to be useful.[4]

Finally, a limitation of this research is that the model only takes into account a single TIS. This is in particular a limitation, because it fails to do justice to the argument in the 'transformational failures' framework that a key question from a transitions perspective is related to choosing between different TIS from the perspective of what is desirable from an overall transition perspective. Moreover, future work can also include further unpacking of the regime concept in the model, to explore in more detail what kind of policy interventions are required to reduce regime resistance. The current model only does this at an abstract level. Future work could focus, for instance, on the different kind of regime dimensions as proposed by Geels (2002): technology, markets, policy, knowledge, industry, culture and infrastructure. An alternative approach could be to mirror the TIS motors so that one represents and emerging TIS and another one represents an incumbent TIS—with interacting linkages between them.

[4] Other methodological tools can also be considered, such as interactive/participatory system dynamics modelling (e.g., Vennix, 1999), in which workshop participants are invited to make conceptual models of particular TIS using system dynamics concepts, and explore specifically the interactions between functions.

6. Conclusion

This paper set out to develop links between the 'failures framework' developed by Weber and Rohracher (2012) and the combined TIS-MLP framework developed by Walrave and Raven (2016). More specifically, we investigated how technological innovation systems respond to policy interventions to overcome transformational failures. We can now draw the following conclusions. By means of a system dynamics simulation model, we find that grand societal challenges benefit the most from policy intervention against reflexivity failures—independent of the transition pathway context. In our model this was approached specifically through a reduction of regime-resistance towards the TIS and additional support for increasing the legitimacy of the TIS. This conclusion implies the need for further work on the ways in which regime resistance can be reduced. In particular, this conclusion is relevant for situations in which the TIS is in a competitive relation with the regime. Because overcoming reflexivity failures is (under the assumptions in our model) the only feasible approach to further stimulate TIS development. Furthermore, we conclude that in transition pathway contexts in which the TIS is in a more symbiotic relation with the regime, policy interventions could also be considered to follow other failure logics, and in particular demand articulation and directionality failure logics, because our results (again taking into account the assumptions we made) show substantial niche market growth in response to such policy interventions. Policy interventions to overcome policy coordination failures were found to have the least positive impact on TIS developments in terms of niche market growth in the context of symbiotic TIS-regime relations. Finally, we conclude that the work in this paper hopefully provides a fruitful starting point for future research on policy interventions for transformational failures, as argued in the previous section.

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