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

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ABSTRACT

The need for challenge-led innovation policies to address grand societal challenges is increasingly recognised at various policy levels. This raises questions how to overcome a variety of 'failures' prohibiting innovations to flourish. A key-line of thought in theory and policy emerged since the late 1990s on the role of system failures, next to more conventional market-failure thinking. More recently, scholarly work introduced the notion of 'transformational failures', which implies an even broader perspective on innovation failures as resting in challenges related to transforming entire systems of production and consumption. This paper combines the literature on Technological Innovation Systems (TIS) with literature on multi-level approaches to sustainability transitions to make a contribution to this debate. In particular, this paper argues that the current literature, so far, has failed to explore how different kinds of policies, or policy mixes, can overcome transformational failures. The paper uses a simulation model (i.e. a system dynamics model) and illustrative examples on electric vehicles to explore relations between transformational failures and (mixes of) policy interventions. A key conclusion is that, in particular in the case where an emerging TIS is in a competitive relation with an incumbent system, overcoming transformational failures can be realised either by directly addressing the incumbent system, for instance by taking away its resources (which may be political challenging). Alternatively, the model results show that a clever mix of policy interventions elsewhere in the system may lead to sufficient performance improvements of the emerging TIS so that it can challenge the incumbent system on its own – albeit with a need for substantial additional resources.

1. Introduction

The need for challenge-led innovation policies to address grand societal challenges is increasingly recognised at various policy levels (Coenen et al., 2015; Steward, 2012). 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. For instance, mobility systems world-wide continue to be predominantly organised around privately owned, fossil-fuel powered cars. These cars are aligned with and embedded in current global production networks, user-practices, fuel and maintenance infrastructures, cultural beliefs around personal freedom and so on. Fossil fuel powered cars, however, have negative externalities, such as implications for the global climate and inner-city pollution. Innovation policies are in place to stimulate the development and diffusion of cleaner cars such as electric vehicles. Following from the above, this requires not just the successful development of a new type of car, but also the transformation of related infrastructures, user-practices, infrastructures, cultural believes and so on. In particular, the literature on 'sustainability transitions' (Markard et al., 2012) has been explicitly conceptualising the dynamics of such transformations through frameworks such as the Multi-Level Perspective (MLP) (Geels, 2002; Rip and Kemp, 1998) and Technological Innovation Systems (TIS) (Bergek et al., 2008; Hekkert et al., 2007; Markard and Truffer, 2008).

The literature on TIS 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.

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(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 TIS functions, as outlined above, effectively allows for diagnosing the performance of a particular TIS. 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.

Similarly, the MLP has become a key-framework in understanding and conceptualising sustainability transitions. This framework has been elaborated in more detail elsewhere (e.g. Geels, 2002). Here we note that the MLP conceptualises transitions is resulting from the interactions between a) incumbent 'socio-technical regimes', which refer to rules and routines embedded in incumbent actor networks, infrastructures and institutions; b) 'niches', which refers to protective spaces that shield and nurture radical innovations; and c) the 'socio-technical landscape', which refers to wider trends and shocks that provide an exogenous environment for niches and regimes. Depending on the timing and type of interactions between niches, regimes and the landscape, transition pathways may differ (Geels and Schot, 2007).

Following this, scholars have engaged in thinking through the implications and rationales for policy intervention for the successful development of sustainable innovations, such as electric vehicles. 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 (Woolthuis et al., 2005; Wieczorek and Hekkert, 2012; van Mierlo et al., 2010; Foxon and Pearson, 2008; Foxon et al., 2005). Another line of research builds upon the MLP to develop reflexive governance approaches (Voss et al., 2006) such as strategic niche management (Kemp et al., 1998; Schot and Geels, 2008; Smith and Raven, 2012) and transition management (Loorbach, 2010; Rotmans et al., 2001). Recently Weber and Rohracher (2012) attempted to combine these lines of reasoning into an elaborated framework on so-called '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 MLP reasoning. Section 2 will elaborate more on this framework.

Whilst this 'transformational failures' framework 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. For instance, how would such interventions actually look like in terms of, for instance, budget size and timing. Which processes of an emerging TIS does such interventions need to target? And how will the impact of these interventions be dependent on resistance and windows of opportunities in wider contexts? Moreover, recent scholarship argues that such policy interventions should be understood in terms of 'mixes' or 'portfolios', which in TIS terminology implies a particular combination of interventions that target multiple TIS functions simultaneously (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016). For instance, rather than focusing support on new knowledge development on battery technology for electric vehicles alone, a policy mixes approach would imply a combination of interventions targeting knowledge development and diffusion, market creation, entrepreneurial experimentation and the shaping of wider legitimacy for electric vehicles. 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 TIS framework. We will explore to what extent different policy interventions, which are inspired by Weber and Rohracher's (2012) transformational failures framework, shape the functional dynamics of a TIS. 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?*

In order to answer this research question, we adopt the system dynamics model by Walrave and Raven (2016). System dynamics modelling is especially suitable for studying complex transition processes, because such models consider problems in terms of feedback loops, time delays, and complex, non-linear relationships (Sterman, 2000). The adopted model is grounded in the concept of 'motors of innovation' (Suurs, 2009) and was developed specifically for studying TIS dynamics in the context of early stage system development. More specifically, the model takes outset in four motors: 'the science and technology push motor', the 'entrepreneurial motor', the 'system-building motor' and the 'market motor'—and the causal relationships that exist within and between these motors. Section 2 will elaborate on these motors. By extending this model, by incorporating policy to address transformational failures, we are able to contribute to the extant literature by: (a) translating the transformational failures framework to the TIS domain and (b) developing and exploring the effectiveness of policy (mixes) directed to counteract 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. Throughout the paper, we will provide illustrative examples on electric vehicles for further clarification of our argument.

2. Transformational interventions in TIS dynamics

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 at least 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 spill-overs that may benefit other firms) and negative environmental externalities (referring to the argument that markets generally do not internalise environmental costs into prices). Following the economics literature, other reasons may be defined, such as improperly defined property rights, externalities, public goods, imperfect competition, imperfect information, inappropriate government intervention, divergence of social and private discount rates (Kahn, 1998).[1] Nevertheless, 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. For instance, even though electric vehicles may at some point reach competitive price levels with gasoline cars, their wider uptake may still be hindered because private firms underinvest in large-scale charging infrastructures. In response, system innovation scholars started to develop additional rationales for policy interventions that go beyond a linear understanding on innovation, which considers the systemic nature of innovation (Smith and Kuhlmann, 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

[1] We thank one of the reviewers for suggesting these additional reasons.

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 to support the successful development and diffusion of those innovations. What is still missing, then, 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' that 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*". In order words, as Foxon and Pearson (2008: 152) argue, transformations towards sustainable development requires policy makers to "*reconcile innovation and sustainable policy objectives*", which raises a range of new challenges, because these may not always be aligned. For instance, innovation policies for improving technological and economic efficiency of electric vehicles will need to be considered in relation to the development of policy frameworks for sustainable and socially just resource extraction of rare earth minerals and massive recycling schemes for batteries, or in relation to reductions in mobility *demand* due to new urban designs and wide-spread use of car-sharing.

Weber and Rohracher (2012) have started to conceptualise such new challenges and complemented the previous rationales of 'market failures' and 'systemic failures' with the notion of 'transformational failures'. They do so by explicitly combining the TIS approach with the MLP on sustainability transitions. Here, 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. TIS 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 legitimizes additional policy intervention. For instance, the development of a TIS around electric vehicles may fail to endogenously include broader sustainability criteria around socially just and sustainable extraction of resources necessary for the production of batteries.
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'. For instance, demand for electric vehicles may remain limited as long as the driving range of electric vehicles remains smaller compared to gasoline cars, because consumers do not include wider sustainability criteria that would benefit electric vehicles sales into their purchase decisions.
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). For instance, making sure that battery production is based on sustainable and socially just resource extractions requires coordination of policies actors across national scales (e.g. between the EU and China), and between innovation policy framework and environmental policy frameworks targeting both car and mining industries. All this implies substantial policy alignment challenges.
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 progress towards broader transformation goals and the development of adaptation strategies. For instance, as the wider diffusion of electric vehicles occurs, new risks and challenges may emerge such as inabilities of current electricity networks to supply peak demand for charging electric vehicles with sustainable electricity.

We believe that this typology of transformational failures provides a useful starting point for legitimising interventions in the dynamics of TIS, in the context of grand societal challenges. Weber and Rohracher (2012), however, are somewhat ambiguous 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 aim to explore these relations between combining TIS literature on 'motors of innovation' literature on transition dynamics in different multi-level contexts, i.e. 'transition contexts'. We first discuss briefly the notion of motors of innovation in more detail, followed by the notion of transition contexts. For a more elaborate discussion in relation to the model used in this paper, see Walrave and Raven (2016).

Motors of innovation refer to interaction patterns between different TIS functions. More specifically, 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. 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. 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 characterised 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 (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. 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, 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. All functions are important in this motor, but the 'creation of legitimacy' is less critical (Suurs, 2009: 223).

In the adopted model (Walrave and Raven, 2016), emerging innovation systems are contextualised with the notions of *regime* and *landscape*, as developed in MLP literature, which provide fruitful avenues for exploring this interplay between innovation system and context (Markard and Truffer, 2008; Bergek et al., 2015). Geels and Schot

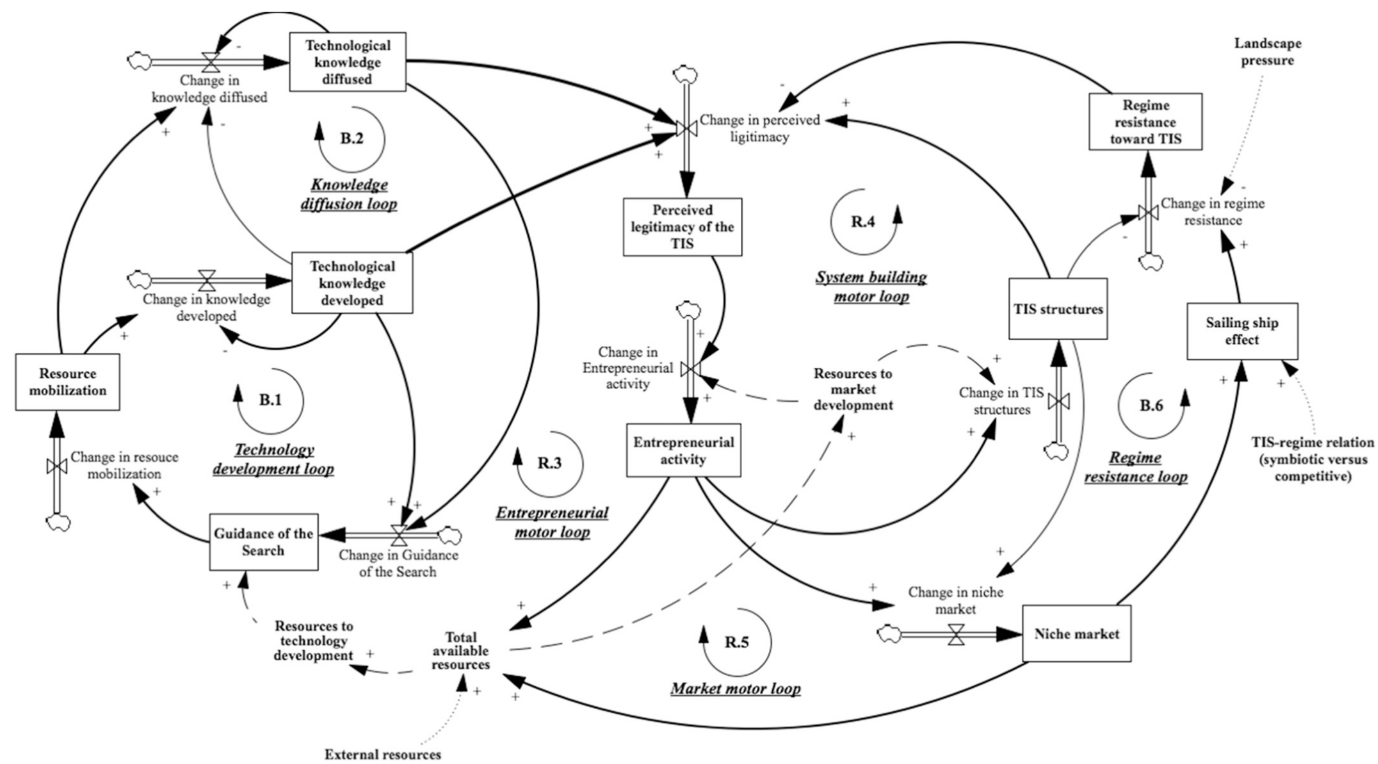

Fig. 1. Stylised overview of the model (adapted from Walrave and Raven, 2016).

(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. An example from electric vehicles here would be a situation in which, for instance, a large increase in global oil price occurs when full electric vehicles are still in a very early stage of development, and where incumbent car producers use batteries as auxiliary device to make gasoline cars more efficient.

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 proactively for alternatives, that is, regime resistance is relatively small. An example from electric vehicles here would be a situation in which a large and persistent price increase in global oil prices occurs when full electric vehicles are still in an early stage of development, but where incumbent car producers no longer believe that efficiency improvements of gasoline cars will be able to deal with such higher fuel prices, and respond by actively searching and developing for alternatives, including but not limited to electric vehicles.

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. An example from electric vehicles would be a situation in which a large increase in global oil prices at a moment when viable niches for electric vehicles have already been established in for instance in environmentally regulated urban contexts, but where car manufacturers strongly resolve to major innovation efforts to make large jumps in the environmental performance of gasoline cars through weight reductions, gas cleaning technologies and fuel efficiency improvements. Market competition between electric vehicles and new, cleaner gasoline cars determines transition dynamics.

Finally, a '*reconfiguration pathway*' refers to a context in which (1) landscape pressures also occur 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. An example from electric vehicles would be a situation in which a large and persistent increase in global oil prices occurs at a moment when viable niches for electric vehicles have already been established, and in which incumbent car manufacturers no longer believe in optimisation of gasoline cars in the long run, which leads to collaborative relations between incumbent car producers and new electric vehicles producers.

The following section will elaborate in more detail on the modelling approach and associated experimental setup.

3. Modelling transformational system failures

In order to study how a TIS responds to policy interventions, directed to overcome transformational failures, we adopt a simulation modelling approach. Formal modelling is increasingly used to study the complex dynamics underlying transitions (e.g. Holtz et al., 2015; Halbe et al., 2015; Walrave and Raven, 2016). Here, we adopt system dynamics modelling, which is especially suitable for investigating dynamically complex phenomenon, 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 policy experiments that are otherwise difficult to test in empirical settings—such is the case here.

Here, we adopt the model developed by Walrave and Raven (2016). This 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. Fig. 1 details the model.

The model consists of six main feedback loops, reflecting the motors of innovation (Suurs, 2009), which subsequently include the seven TIS 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 recognising 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) (see 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 MLP; *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 such failures and explore to what extent policy interventions, inspired by transformational failures, shape the dynamics of TIS.

We assume the following relations between transformational failures and particular policy interventions. In each case, we distinguish between a 'primary' TIS 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 the development of a shared vision concerning the goal and direction of the development (Weber and Rohracher, 2012), such as the development of collective political visions on the future design and use of electric mobility. This resonates with the development of the TIS *internal* function 'Guidance of the search' (see the '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 towards the TIS, in order to gain support for the future of the TIS from powerful regime incumbents, such as R&D support for incumbent car manufacturers. 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; Kemp et al., 1998), such as only allowing zero-emission vehicles in inner-city zones. Within such protected environments "actors can learn about the new technology and expectations 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 towards the TIS should be managed, for instance by making exceptions to zero-emission zones in inner-cities for delivery vehicles. 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. 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 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. 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). In the case of electric vehicles, this would, for instance, refer to attempts to align policy frameworks and industry standards for smart grids with policy frameworks and industry standards for electric vehicle in such a way that the latter can act as temporary storage for renewable electricity production in households. 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). For instance, in the case of electric vehicles this would refer to attempts to lure incumbent car manufacturers into the production of electric vehicles through collaborative scenario studies and engaging them in participatory technology assessment approaches, or through more aggressive policies such as enforcing very high emission standards, which can only be realised with electric vehicles. Furthermore, reflexivity draws on an evidence-based approach that is needed to legitimise policy interventions and, as such, bring about legitimacy for the TIS.[2] Therefore, we argue that overcoming reflexivity failures require *primarily* a reduction of regime resistance towards TIS in combination with *supporting* the TIS function 'Creation of legitimacy'.

[2] Whilst not supported in the formal model, a portfolio approach might also be employed to reach this goal.

Concluding, in this paper we postulate the following links between the failures framework by Weber and Rohracher (2012) and policy interventions 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'.*

Henceforth, we refer to these intervention as 'directionality intervention', 'demand articulation intervention', 'policy coordination intervention' and 'reflexivity intervention' respectively.

3.1. Experimental setup

Our experiments set out with the 'hybrid' resourcing condition (see Walrave and Raven, 2016). A hybrid resourcing condition implies that a TIS initially draws substantially on technology-oriented resources, whilst in later development phases it draws on significant market-oriented resources. Resources are available over a period of 15 years—and may originate from government funding or private capital. Whilst the hybrid setup was found to be most efficient for early stage TIS development, this resourcing condition is by no means a guarantee for success (Walrave and Raven, 2016).

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 and are 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 indicated by a sustained negative trend in niche market growth—potentially due to transformational system failures.[3] 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 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. These sensitivity analyses are included in the model appendix.

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 pathway context. 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.[4]

4. Results

Figs. 2, 3, 4, and 5 depict the results of the experiments; for de-alignment and re-alignment, reconfiguration, transformation, and technological substitution respectively. These figures denote the results for 'Niche market' (see Fig. 1), which is considered as an indicator for the viability of the emerging 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 base scenario to which the *if-then* analyses may be compared. 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 towards TIS). As such, both reference runs (in Figs. 2 and 3) already resulted in a sustainable TIS as the result of the initial resource provisions (also see Walrave and Raven, 2016).[5]

First, overall, the results indicate that the different policy interventions designed 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 strategic 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 that targets multiple TIS functions simultaneously (Walrave and Raven, 2016; Weber and Rohracher, 2012).

Second, the different policy interventions, however, have varying effects on niche market growth. More specifically, from the four interventions, the reflexivity intervention results in the largest niche market growth—independent of contextual situation. Furthermore, a reflexivity intervention is the only one effective in the context of an unfavourable TIS-regime relationship (see Figs. 4 and 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 positive TIS 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 overcoming a reflexivity failure, and therefore simulating the *self-reinforcing* development of the TIS, is critical.

Third, notably demand articulation interventions 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 Figs. 2 and 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, in which incumbent actors resist the emergence of a new TIS. The reason for this is that policy targeting demand articulation failure is arguably not likely to

[3] 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.

[4] Note that a comprehensive model appendix, detailing all amendments to the original model to facilitate the proposed experiments, is available upon request from the authors.

[5] The randomness in our results, as visible in the figures below, originates from a pink noise process that was part of the original model. This structure was maintained in our simulations for reasons of comparability.

Table 1
Transformation system failures in relation policy intervention.

	Intervention	Primary function targeted by policy intervention	Supportive function targeted by policy intervention
	Additional resource distribution	80%	20%
1	Directionality intervention	'Guidance of the search'	'Regime resistance towards TIS'
2	Demand articulation intervention	'Market formation'	'Regime resistance towards TIS'
3	Policy coordination intervention	'TIS Structures'	'Regime resistance towards TIS'
4	Reflexivity intervention	'Regime resistance towards TIS'	'Perceived legitimacy of the TIS'

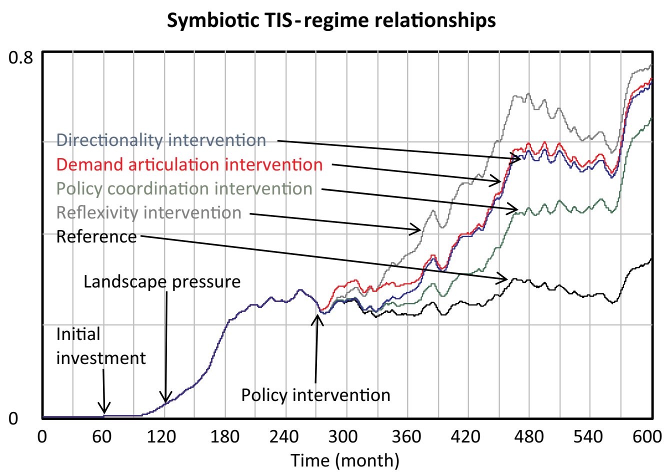

Fig. 2. Context: De-alignment and Re-alignment. Results for 'Niche market'.

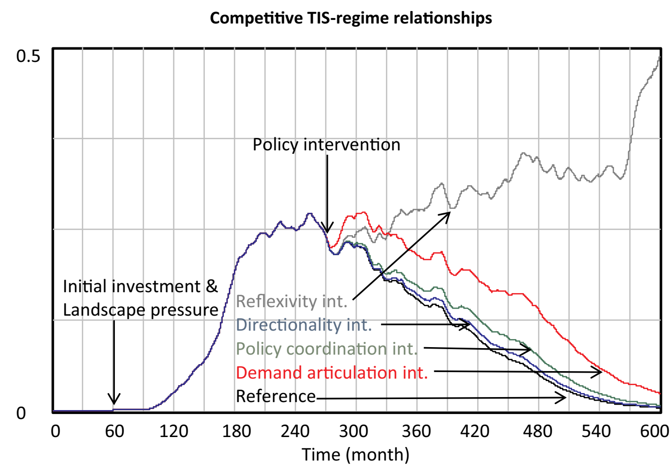

Fig. 4. Context: Transformation. Results for 'Niche market'.

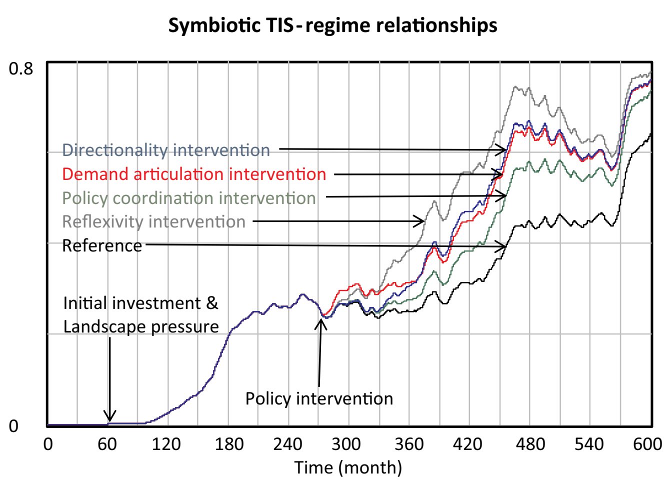

Fig. 3. Context: Reconfiguration. Results for 'Niche market'.

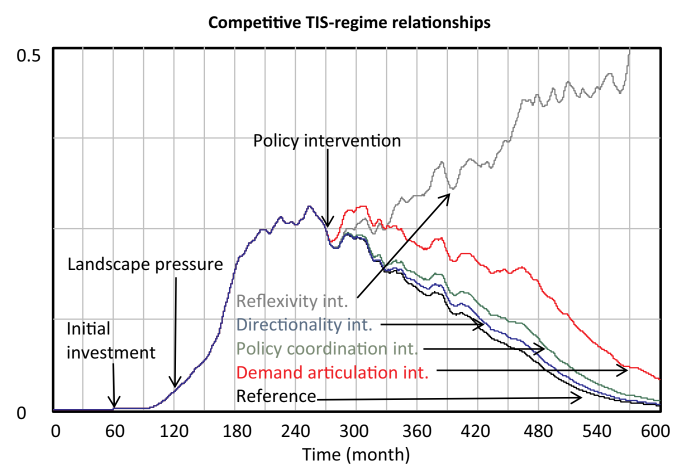

Fig. 5. Context: Technological substitution. Results for 'Niche market'.

overcome an unfavourable TIS-regime relationship fast enough, as it often takes too much time to lure regime actors into a more positive attitude towards the TIS on the basis of relatively small niche markets alone. As such, once policy support ends, the TIS declines again (as illustrated by Figs. 4 and 5).

Fourth, the results suggest that in case of 'de-alignment and re-alignment' and 'reconfiguration' contexts (i.e. in cases where regime actors are positive towards the emerging TIS) there are different interventions that policy makers can use for stimulating the TIS, whilst achieving more or less similar results. Indeed, the directionality and demand articulation interventions show very similar dynamics. The policy coordination intervention also results in similar niche growth, although this intervention is, relatively speaking, the least effective. Nevertheless, our results suggest that in case of a symbiotic TIS-regime relationship supporting either the guidance of the search, market formation or TIS structures may very well result in highly similar, positive results.

Based on these results, we conducted a post-analysis. More specifically, we developed more complex policy mixes, or policy portfolios, where different types of failures were targeted simultaneously. Here, we considered the reflexivity intervention as the new base scenario. This is because this policy intervention shows the best performance, but may in practice also be the most challenging in political terms, because it heavily relies on policies that lure incumbent actors into a more positive stand towards an emerging innovation system, which may threaten their core business. As such, for this post-analysis, we study all possible combinations of the earlier defined policy interventions, whilst keeping the available resources constant, in an attempt to match the performance of the reflexivity intervention—for every transition context. In other words, our main goal was to see if (more complex) policy portfolios are capable of outperforming the (politically more difficult)

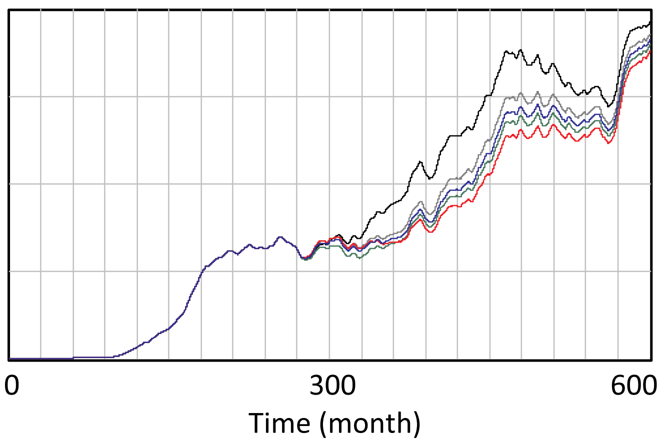

Fig. 6. Context: De-alignment – Re-alignment. Results for 'Niche market'.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reflexivity intervention.

More specifically, we studied the following policy mixes: (1) directionality intervention & demand articulation intervention, (2) directionality intervention & policy coordination intervention, (3) demand articulation intervention & policy coordination intervention, and (4) directionality intervention, demand articulation intervention & policy coordination intervention. For every policy mix, we assume an equal distribution of the available resources over the involved interventions.

Figs. 6, 7, 8, and 9 denote the results of this post-analysis—per transition context—for the dynamic behaviour of the 'Niche market'. In these figures, the black lines denote the results of the original reflexivity intervention (i.e. the new base case). The relative performance of the policy mixes 1, 2, 3, and 4 are depicted by the grey, green, red, and blue lines respectively. The results indicate that the policy mixes match the performance of the reflexivity intervention in case of a symbiotic TIS-regime relationship (Figs. 6 and 7), but *not* in case of a competitive relationship (Figs. 8 and 9).

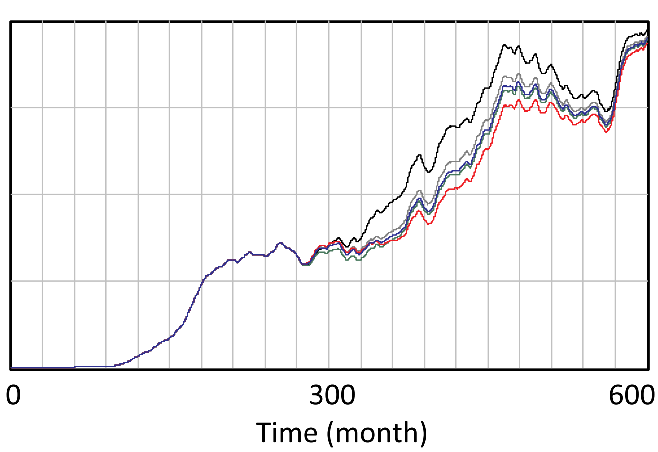

Fig. 7. Context: Reconfiguration. Results for 'Niche market'.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

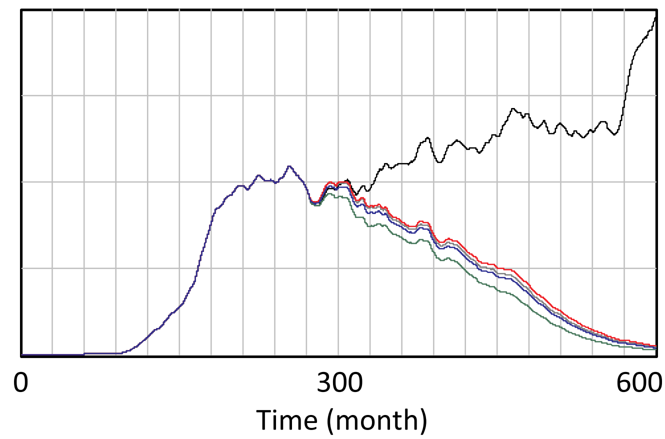

Fig. 8. Context: Transformation. Results for 'Niche market'.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

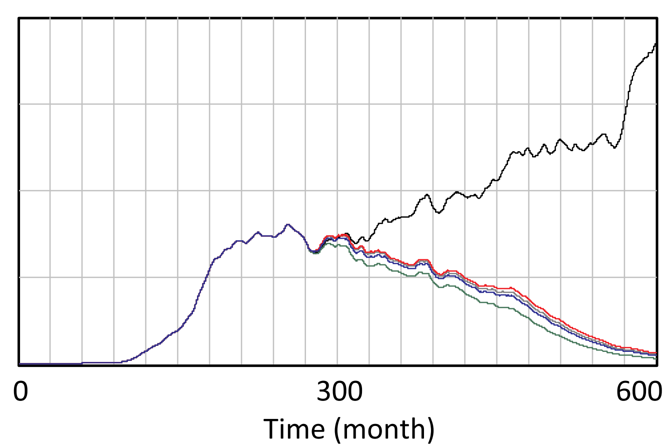

Fig. 9. Context: Technological substitution. Results for 'Niche market'.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Subsequently, we studied how many additional resources would be required, in case of a competitive TIS-regime relationship, for the described policy mixes to match the performance of the reflexivity intervention. Here, our experiments illustrate that a resource increase of about 300% is necessary—except for the directionality & policy coordination intervention mix, which, despite the significant resource increase, remains rather ineffective (see the green lines in Figs. 10–13). Figs. 10 and 11 denote the results for the transformation context, for a 250% and 300% resource increase respectively and Figs. 12 and 13 provide the results for the technological substitution context.

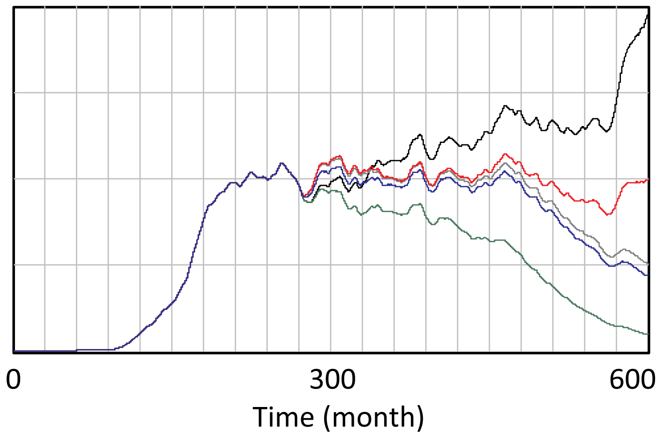

Fig. 10. Context: Transformation. 250% Resource increase. Results for 'Niche market'.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

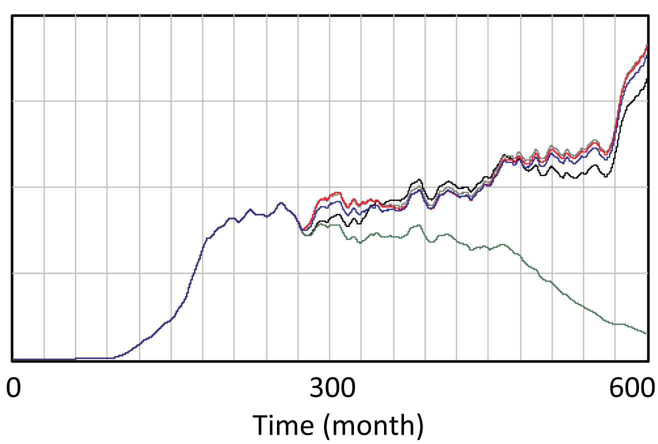

Fig. 11. Context: Transformation. 300% Resource increase. Results for 'Niche market'.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

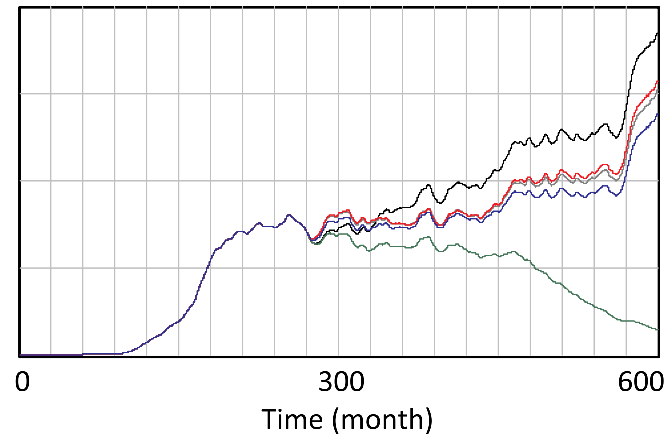

Fig. 12. Context: Technological substitution.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

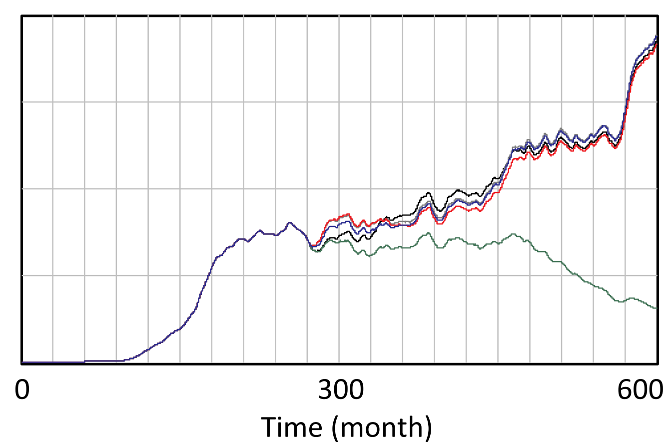

Fig. 13. Context: Technological substitution.
(1) Grey: Directionality intervention & demand articulation intervention.
(2) Green: Directionality intervention & policy coordination intervention.
(3) Red: Demand articulation intervention & policy coordination intervention.
(4) Blue: Directionality intervention, demand articulation intervention & policy coordination intervention.
(5) Black: Reflexivity intervention (no resource increase). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

This paper set out to investigate the relation between Weber and Rohracher's (2012) transformation failures and TIS dynamics by exploring how policy interventions may overcome such failures. Whilst the '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. As such, we set out to investigate *how technological innovation systems respond to policy interventions directed to overcome transformational failures?* By means of a formal model, we explore relations between transformational failures and policy interventions, and study the ways in which they influence the development of TIS in various transition contexts. Our contribution to the literature is twofold: First, we carry over the transformational failures framework to the TIS domain, and second, we develop and explore the effectiveness of policy interventions directed to counteract transformational failures.

We develop policy interventions, based on the TIS functions, directed to overcome transformation failures. By doing so, we carry the transformation failures framework over to the TIS domain. More specifically, we postulate that *Directionality failures* can be overcome by providing support for the function 'Guidance of the search' and the reduction for regime resistance towards TIS. *Demand articulation failures* can be overcome by providing support for the function 'Market formation' and reducing regime resistance towards TIS. *Policy coordination* *failures* can be overcome by providing support for 'TIS structures' and reducing regime resistance towards TIS. Finally, *Reflexivity failures* can be overcome by reducing regime resistance towards TIS and by providing support for the function 'Legitimacy'.

By means of a system dynamics model (adapted from Walrave and Raven, 2016), we explore these intervention strategies. The 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. More specifically, we find that grand societal challenges benefit the most from reflexivity interventions. In particular, this conclusion is relevant for situations in which the TIS is in a competitive relation with the regime. This conclusion implies the need for more work on ways in which regime resistance can be reduced (Geels, 2014). Furthermore, we conclude that in those transition pathway contexts where the TIS is in a more symbiotic relation with the regime, policy interventions that follow other logics can also be considered. Of particular interest may be the demand articulation and directionality interventions, because our results indicate substantial niche growth in response to such policy interventions.

Furthermore, our post-analysis illustrated that policy mixes, or portfolio's, which target multiple transformation failures simultaneously, might provide a viable alternative to the politically difficult reflexivity intervention. Especially in situations where the TIS is in a competitive relationship with the dominant regime can such policy mixes serve as effective alternatives to the reflexivity intervention—although substantially more resources are likely required. We conclude that this insight provides fruitful input for future work. For instance, scholar could develop and investigate policy mixes (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016) that are specifically attuned to the context in which they are meant to operate, which might enhance the resource effectivity of the intervention.

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 critically 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, in particular when attuned to specific ongoing cases and contexts.[6]

In this respect, another contribution of this paper lies in the further development of the system dynamics model by Walrave and Raven (2016). Here, our work adds to the upcoming field of transitions modelling (also see Holtz et al., 2015 and Halbe et al., 2015 for a more in-depth discussion on modelling transitions). Future research may make use of this 'updated' model to further investigate TIS dynamics. Here, a promising avenue for future work may be to make the model more context specific by calibrating it to a specific TIS.

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) and the TIS literature, 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 (see e.g. Walrave, 2016).

Second, 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.

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 carry over the failures framework to the TIS domain, by developing interventions, targeted against such failures, in terms of TIS functions. Furthermore, we investigated how a TIS responds to these policy interventions. We hope that this paper provides a fruitful starting point for future research on (mixes of) policy interventions for transformational failures.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2018.05.008.

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[6] 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.

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