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A complex systems methodology to transition management

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Abstract There is a general sense of urgency that major technological transitions are required for sustainable development. Such transitions are best perceived as involving multiple transition steps along a transition path. Due to the path dependent and irreversible nature of innovation in complex technologies, an initial transition step along some preferred path may cut off paths that later may turn out to be more desirable. For these reasons, initial transition steps should allow for future flexibility, where we define flexibility as robustness regarding changing evidence and changing preferences. We propose a technology assessment methodology based on rugged fitness landscapes, which identifies the flexibility of initial transition steps in complex technologies. We illustrate our methodology by an empirical application to 2,646 possible future car systems.

Keywords NK-model · Complexity · Flexibility · Irreversibility ·
Path dependence · Transition path · Transition management ·
Sustainable development · Car technology

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Abbreviations
CBG   Compressed biogas
CCS   Carbon capture and sequestration
CGH_2 Compressed gaseous hydrogen
CNG   Compressed natural gas
DME   Dimethyl ether
FCV   Fuel cell vehicle
GHG   Greenhouse gases
ICEV   Internal combustion engine vehicle
LCG   Well-to-tank system: Large, centralized, gas-pipeline
LCP   Well-to-tank system: Large, centralized, pipeline
LCT   Well-to-tank system: Large, centralized, truck
LH_2 Liquified hydrogen
LPG   Liquified petroleum gas
MLG   Well-to-tank system: Medium, local, gas-pipeline
MLP   Well-to-tank system: Medium, local, pipeline
MLT   Well-to-tank system: Medium, local, truck
NG   Natural gas
SO   WTT system: Small, on-site
WTT   Well-to-tank
WTW   Well-to-wheel

1 Introduction

Technology assessment traditionally focuses on comparing the desirability of alternative technological options. In such a perspective, the transition path to be followed in the future is dictated by the alternative that is preferred at present. This approach to technological transitions faces two problems. First, the future performance of alternative technological systems is uncertain. Due to the path dependent and irreversible nature of technological development (David 1985; Arthur 1989; Cowan 1990), initial transition steps along a particular path may cut off alternative paths, which may turn out to be more desirable at a future moment in time. This means that, if new information becomes available that favors an alternative technological system, it will be difficult to re-orient the transition path into a new direction. Second, societal preferences may change during a transition process (Pinch and Bijker 1984). Such a change may induce a reversal of the transition process wasting time and resources. For these reasons, we argue that initial transition steps should be flexible, where we define a flexible transition strategy as a strategy that is robust with regard to changing evidence and changing preferences.

Transitions in large technical systems such as transport and energy technologies are characterized by irreversibility and path dependence. Changes in such systems often involve high sunk costs causing such investments to be

expensive to reverse. To take into account this path dependence and irreversibility inherent to technological transitions, we propose a complex systems approach to technology assessment based on the concept of rugged fitness landscapes (Kauffman 1993). Complex technological systems are characterized by rugged fitness landscapes with local optima reflecting compromises between conflicting constraints. In this framework, flexibility can be defined in two ways. First, initial transition steps should be robust in the case of changing evidence regarding the 'fitness' (performance) of alternative technological options. Changing evidence can be dealt with by maximizing the number of local optima that can still be reached after an initial transition step and by maximizing the number of possible paths towards each local optimum after an initial transition step has been taken. Second, initial transition steps should be robust to changing preferences to avoid a reversal of the transition process. Changing preferences can be dealt with by pursuing an initial transition step that yields an improvement regarding all preferences (Pareto improvement).

We will proceed as follows. Section 2 describes the complex systems model based on rugged fitness landscapes. We will explain the logic underlying rugged fitness landscapes using a simple simulation using the NK algorithm (Kauffman 1993). Section 3 introduces the two notions of flexibility regarding initial transition steps using the example of NK fitness landscapes. In Section 4, we apply the flexibility measures to empirical data describing all possible transition paths in a design space comprising 2,646 alternative car systems. We emphasize that the application to car technology data serves an illustrative purpose more than a predictive purpose. Section 5 concludes.

2 NK fitness landscapes

Complex technological systems contain several interdependent subsystems that function in a coherent manner (Rosenberg 1969; Simon 1969; Hughes 1983; Vincenti 1990; Silverberg and Verspagen 2005). Interdependencies between subsystems render the performance or *fitness* of the overall system dependent on the specific combination of the subsystems. All possible combinations form the state space or *design space* of the technological system. The combinatorial logic of assembling systems from subsystems implies that the number of possible designs that can be assembled from only a small set of subsystems is large. For example, a system with only ten elements, each of which can be designed in two ways, has a design space of $2^{10} = 1,024$ possible designs. Depicting technological change as a search process within a design space captures the idea that future technological systems can be represented as combinations of known subsystems. Empirical studies of technological change have shown that many innovations indeed occurred through the combination of existing subsystem technologies (Frenken 2006). Complex systems theory provides us with models to study the effects of interdependencies among subsystems on combinatorial search processes.

Fig. 1 A design space with
$N = 3$, $K = 2$ and fitness
function f

1 2 3	f_1	f_2	f_3	f
000:	0.6	0.5	0.4	0.5
001:	0.1	0.3	0.5	0.3
010:	0.1	0.4	0.1	0.2
011:	0.4	0.7	0.7	0.6
100:	0.9	0.8	0.7	0.8
101:	0.6	0.8	0.4	0.6
110:	0.2	0.6	0.4	0.4
111:	0.9	0.6	0.6	0.7
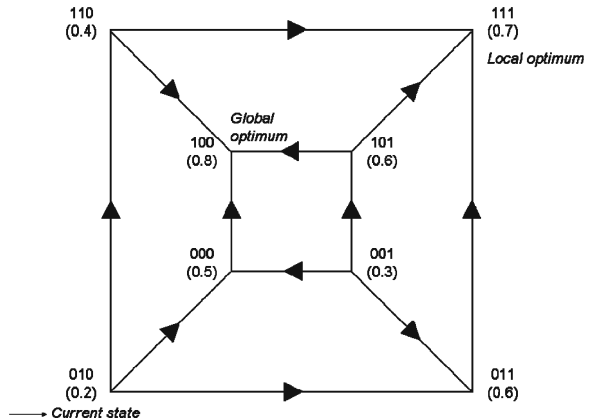
One influential model is the *NK*-model (Kauffman 1993).[1] We introduce
this model here for didactic purposes, yet it is important to recognize that
our empirical methodology does not depend on the assumptions underlying
the NK-model. The complexity of a system with N subsystems is indicated
by K that refers to the number of dependency relations between elements.
The possible value of K ranges from its minimum $K = 0$ to its maximum $K = N - 1$. If the performance of subsystems is not affected by other subsystems,
we have $K = 0$, while if the performance of subsystems is affected by all
other subsystems, we have $K = N - 1$. In the case of minimum complexity,
the fitness of each subsystem is determined independently from the state of
other subsystems, while in the case of maximum complexity, the fitness of
each subsystem is different for each different combination of subsystems. Note
that real-world systems will typically be characterized by intermediate levels
of complexity (Simon 2002).

Figure 1 gives an example of a design space of a technological system
with three subsystems ($N = 3$), where each subsystem can be designed in
two different ways. The total number of states in this design space amounts
to $2^3 = 8$ technology designs. The fitness of each particular subsystem is
dependent on the choice of the other two subsystems ($K = 2$), as the fitness
of each subsystem is different depending on the choice of design for the other

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[1]For a review of NK-models in the context of technological innovation, see Frenken (2006).

subsystems.[2] Following Kauffman ([1993](#)), the fitness value for each subsystem in each specific combination of subsystems can be simulated by random draws from a uniform distribution between 0 and 1. We thus need to draw three random numbers for each of the eight different designs as is done in Fig. [1]. The fitness of the system as a whole can then be derived as the mean of the fitness values of the subsystems.[3] In Fig. [1], state 100 is a global optimum and state 111 is a local optimum. Global and local optima in the design space correspond to peaks in the fitness landscape (hence the metaphor of rugged fitness landscapes). A global optimum is a local optimum that has a superior fitness compared to all other designs, while a local optimum is a design that is superior compared to its neighboring designs, but not compared to all possible designs. Thus, a global optimum is also a local optimum, while a local optimum is not necessarily globally optimal.

Having specified a design space and the corresponding fitness values (the 'fitness landscape'), one can understand technological change as a move from one design x to a new design y in the design space. We make two assumptions. First, we assume that only one subsystem is allowed to change at each time, which means that each subsystem innovation can be represented as a move to a 'neighboring' design along one of the axes in the design space. The assumption that technological transitions consist of a series of changes in subsystems is supported by the observation that, at least for large technological systems, a change in a single subsystem is very costly and can easily take 5–10 years to complete. Second, we assume that a move in design space only occurs if this move does not decrease the fitness f of a technological system, hence, the metaphor of 'hill-climbing' (Kauffman [1993](#)). Since a change in one subsystem is very costly and time-consuming, one can expect any subsystem change that decreases fitness to be socially unacceptable (thus excluding the strategy of 'one step back, two steps forward'). This assumption is supported by the observation that changes in any subsystem often involve durable investments in infrastructure which make these changes expensive to reverse. In the following, we will call each innovation in a single subsystem a *transition step*, and a series of transition steps a *transition path*.

The shape of the fitness landscape determines the possible transition paths. In the simulation example, once a series of innovations ends up in local optimum 111, it becomes impossible to make the transition to the global optimum 100. A transition towards a local optimum is irreversible, as any move away from a local optimum would imply a decrease in performance. A transition path may thus well become 'locked in' into a local optimum. Transition paths are also characterized by path dependence. For example, if

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[2]An implicit assumption of the NK-model holds that the number of subsystems equals the number of fitness values. This assumption can be removed in a generalized NK-model without changing the logic of fitness landscapes (Altenberg [1994](#)).

[3]In the context of technological innovation, system elements correspond to the technical characteristics of a design and the fitness values to service characteristics (Saviotti and Metcalfe [1984](#)).

the first transition step is 010→011, the only remaining transition step from 011 is 011→111. An alternative transition path starts from the transition step 010→000, from which the only second step is 000→100. A myopic search process is thus path dependent in the sense that early decisions determine the scope of future decisions. Figure 1 also shows that there can be multiple paths to the same optimum. In the example, the local optimum can be reached in two ways: via 010→011→111 and via 010→110→111. The global optimum can also be reached in two ways: via 010→000→100 and via 010→110→100. Fitness landscapes for larger design spaces will typically be characterized by many possible uphill paths towards optima of different lengths, a property that we will explore below.

3 Flexibility in technological transitions

We will now use the properties of rugged fitness landscapes to derive three flexibility measures that can be used to assess the desirability of the first transition step while taking into account future uncertainties. The first two measures are based on uncertainty regarding current evidence. An important source of uncertainty in technology assessment is whether the fitness assigned to each possible design in design space is accurate. Forecasting models are necessarily based on current assumptions about technological progress, which later may turn out to have been misinformed. History is full of examples in which commonly held expectations regarding future technological progress turned out to be plain wrong.[4]

The flexibility of a first transition step can be expressed in terms of the number of options it leaves open if evidence about fitness changes over time. In the following, we define *changing evidence* as evidence that a particular design *s*, which previously was thought to have some fitness *f*, actually has zero fitness. This is a stylized way to say that the changing evidence convinces the decision-maker no longer to pursue any transition path that involves design *s*.

If changing evidence concerns an optimum towards which the search process is heading, flexibility is desired so as to be able to reorient the search process towards an alternative optimum. Consider again Fig. 1. If a transition path is chosen towards the global optimum 100, transition path 010→000→100 would normally be preferred over 010→110→100, because the fitness of the intermediate design is higher for 010→000→100 ($f(000) = 0.5$) than for 010→110→100 ($f(110) = 0.4$). However, after 010→000, the only remaining transition step is 000→100, while after 010→110, one can still choose between 110→100 or 110→111. This means that, if new evidence becomes available after the first transition step 010→000, that design 100 has zero fitness, the

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transition process gets stuck at 000. The alternative transition path to 100 via 110, however, can still be reoriented towards local optimum 111 if the fitness of 000 turns out to be zero. We can thus define flexibility according to this principle of 'no regret' as the number of different optima that can be reached after the initial transition step has taken place. We will call this type of flexibility *design flexibility*. In the example in Fig. 1, transition steps 010→000 and 010→011 have design flexibility equal to 1 and the transition step 010→110 has design flexibility equal to 2.

Another way to explain design flexibility is in graph-theoretical terms. A fitness landscape can be represented as a network (graph) with each node representing a design and each directed link (arc) representing an up-hill move from one design to a neighboring design. The design flexibility of a node equals the number of local optima that can be reached following a path of directed links. The Appendix provides the formal expression.

If the changing evidence does not regard the fitness of an optimum, but of designs that lie on a transition path towards an optimum, the transition path towards an optimum becomes blocked at some point along the path. This is implied by the assumption that an innovation is only accepted if it does not decrease fitness. If, after the initial transition step, new evidence becomes available that the next transition step would actually lead to zero fitness, the transition process comes to an end, unless there are alternative paths towards an optimum. The number of alternative paths towards an optimum can thus be considered a flexibility measure. The second flexibility measure, which we call *path flexibility*, therefore counts the number of different paths that lead to an optimum given an initial transition step. In the simulation in Fig. 1, the path flexibility of all three initial transition steps regarding any optima that can be reached after the initial step, equals 1. A second simulation provided in Fig. 2 shows an example of a fitness landscape, where the initial transition step 010→011 has a path flexibility of 2, since the global optimum 101 can be reached either via path 011→001→101 or via path 011→111→101. Path flexibility can also be expressed in graph-theoretical terms. The path flexibility of a node regarding a specific local optimum is the number of paths of directed links between this node and the local optimum. The Appendix provides the formal expression.

The third flexibility measure is not based on uncertainty due to changing evidence but on uncertainty caused by changing preferences. In our discussion so far, we reasoned from a single fitness function, for example, a 'social welfare function'. Such reasoning presupposes that consensus exists in a society on how alternative technologies should be assessed. However, more often than not, different social groups have different valuations of a technology (Pinch and Bijker 1984). For example, some actors prefer a future car system that is less expensive than the current one. Other actors may emphasize that a future car system should be less polluting, even if the costs of such a system would be higher than the costs of the current system. We take multiple preference sets into account by viewing technological change as taking place in a single design space with multiple fitness functions attached to it.

Fig. 2 An alternative fitness function g

	g_1	g_2	g_3	g
1 2 3				
000:	0.1	0.1	0.1	0.1
001:	0.5	0.5	0.8	0.6
010:	0.4	0.1	0.1	0.2
011:	0.5	0.5	0.5	0.5
100:	0.3	0.2	0.1	0.2
101:	0.8	0.7	0.9	0.8
110:	0.1	0.1	0.1	0.1
111:	0.5	0.7	0.6	0.6
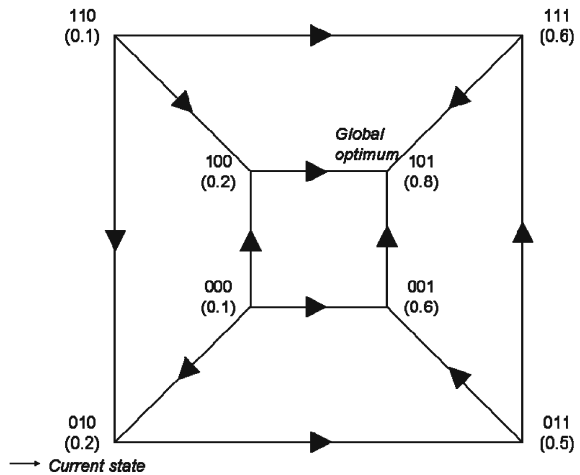
In Fig. 2, an alternative set of fitness values is presented for the same design space as in Fig. 1 reflecting the valuation of a second social group. We can now define a flexible initial transition step as a step that meets both sets of preferences at the same time, i.e., a transition step that increases both fitness f and fitness g. Thus, if the initial transition step is described as $x \to y$, a flexible strategy is one which holds that both $f(x) \geq f(y)$ and $g(x) \geq g(y)$. In the examples of Figs. 1 and 2, such a strategy would lead to the path: 010→011. One could call this strategy a win-win strategy, also known as a Pareto improvement. Such a strategy is flexible in the sense that, if the power balance between different groups having different preferences shifts over time (e.g., a change in government), it will not lead the decision-maker to undo the initial transition step and to reverse the transition process. We call this type of flexibility of the initial transition step *preference flexibility*.

4 The transition towards a sustainable car system

In the remainder, we will apply the three flexibility measures to data on fitness values of alternative future car systems. A transition path from the current

oil-based individual transportation system to a more sustainable system meets the assumptions underlying the framework just described:

- Complexity: the system is complex in that it consists of subsystems, which function interdependently but can be changed independently
- Uncertainty: the fitness of alternative designs can be assessed in principle *ex ante*, but is highly uncertain
- Myopia: any technological transition will most likely occur in a series of myopic rather than coordinated transition steps in subsystems, because any change in a sub-system is a very costly and lengthy process
- Multiple preferences: different social groups apply different evaluation criteria to assess the desirability of alternative options

In order to apply our flexibility measures to assess alternative transition steps towards a future sustainable car system, we proceed as follows. First, we construct the design space of alternative future car systems. We then assign to each alternative design one fitness value reflecting the energy efficiency as a proxy of its economic performance and one fitness value reflecting the reduction in greenhouse gas (GHG) emissions as a proxy for climate performance. We assume there are two dominant social groups with different preferences, with one group aiming to reduce the energy requirements of cars (*economic*) and another group aiming to reduce GHG emissions (*climate*). For both fitness criteria, we derive the global and local optima. Then, we compute the three flexibility measures for each up-hill initial transition step. From the results, we draw conclusions regarding the desirability of alternative transition steps.

4.1 Design space

Technology assessment studies regarding future car systems generally use a well-to-wheel (WTW) perspective to describe an alternative technological system in terms of its subsystems. We use data from previous WTW studies to build the design space. To classify each of the subsystems, a high level of aggregation is chosen, thus ignoring sub-sub-systems within each subsystem. Based on previous studies, we distinguish five major subsystems following the WTW logic: the energy source (seven options); the application of carbon capture and sequestration (CCS; two options); process scale, process location and distribution to filling station (seven options); car fuel (nine options); and vehicle type (three options). The WTW system including all options per subsystem is shown in Fig. 3.

All possible combinations between alternative subsystem designs form the WTW design space representing possible future car systems. Even for this high level of aggregation with only five subsystems, there already exist $7 \cdot 2 \cdot 7 \cdot 9 \cdot 3 = 2,646$ theoretical combinations of energy sources, CCS, distribution systems, fuels and vehicles. In this design space, the current dominant design is classified as crude oil, no CCS, large, centralized truck distribution, gasoline fuel and internal combustion engine.
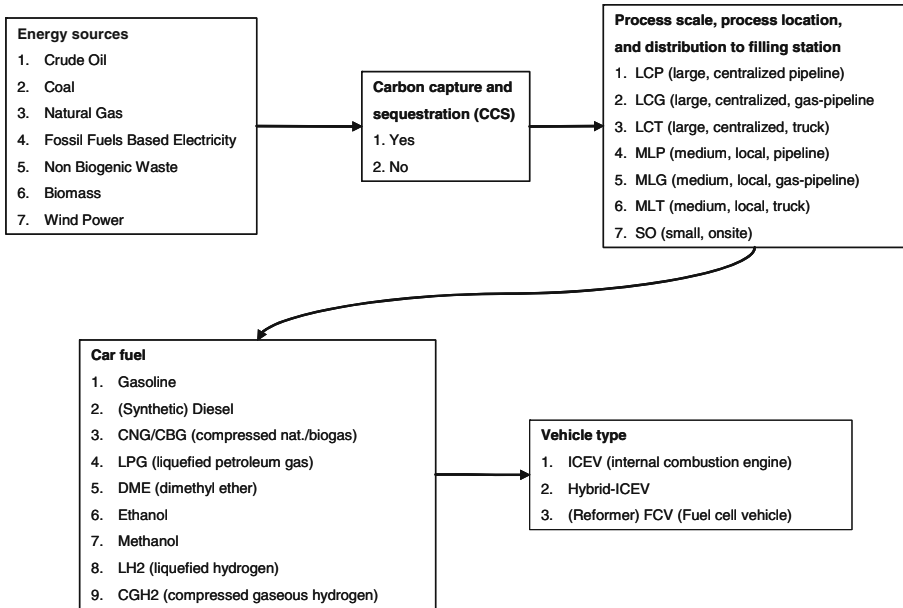
Energy sources
1.   Crude Oil
2.   Coal
3.   Natural Gas
4.   Fossil Fuels Based Electricity
5.   Non Biogenic Waste
6.   Biomass
7.   Wind Power

Carbon capture and sequestration (CCS)
1. Yes
2. No

Process scale, process location, and distribution to filling station
1.   LCP (large, centralized pipeline)
2.   LCG (large, centralized, gas-pipeline)
3.   LCT (large, centralized, truck)
4.   MLP (medium, local, pipeline)
5.   MLG (medium, local, gas-pipeline)
6.   MLT (medium, local, truck)
7.   SO (small, onsite)

Car fuel
1.   Gasoline
2.   (Synthetic) Diesel
3.   CNG/CBG (compressed nat./biogas)
4.   LPG (liquefied petroleum gas)
5.   DME (dimethyl ether)
6.   Ethanol
7.   Methanol
8.   LH2 (liquefied hydrogen)
9.   CGH2 (compressed gaseous hydrogen)

Vehicle type
1.   ICEV (internal combustion engine)
2.   Hybrid-ICEV
3.   (Reformer) FCV (Fuel cell vehicle)

Fig. 3 Subsystems of the WTW system

4.2 Fitness landscapes

We assess the fitness (or performance) of each WTW system in two dimensions reflecting two preferences: WTW energy requirements per kilometer driven and WTW GHG emissions per kilometer driven. The first we call efficiency fitness and the second climate fitness. Efficiency fitness is important given concerns about the availability and increasing prices of (fossil) fuel resources, whereas climate fitness is important given concerns about the negative climate impact of our current fossil-fuel based car system. The two fitness values of each possible technological system are taken from Schwoon (2006), which in turn is based on the WTW analyses available (GM et al. 2002; Ahlvik and Brandberg 2001; EC-JRC 2006).

Only a minority of 987 out of the 2,646 designs have a fitness value equal to or higher than the fitness value of the current dominant design in terms of one or both fitness criteria. In order to find the local optima, we check which designs could not be improved by a change in a single subsystem regarding efficiency fitness or climate fitness. As the fitness values are rounded, neighboring designs with identical performance occur.[5] Thus, optima can consist of more than one design, which are neighboring in the sense that they are no more than

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[5]Schwoon (2006) choose to round fitness values to account for some of the uncertainty in the technical data on the expected performance of each technology. Note that rounding means that agents engage in what is called "noisy search" (Levinthal 1997).

Table 1 Optima of WTW systems

	Current system	Global optimum with regard to efficiency	Local optimum *A* with regard to efficiency	Local optimum *B* with regard to efficiency	Global optimum with regard to environment
Energy source	Crude Oil	Crude Oil	Wind power	NG	Biomass
CCS	No	No	No	No	Yes
Distribution	LCT	LCG *or* LCT	MLT	LCG *or* LCT *or* MLG *or* MLT *or* SO	LCT
Fuel	gasoline	CGH2	LH2	CNG	LH2
Vehicle	ICEV	FCV	FCV	Hybrid-ICEV	ICEV *or* Hybrid-ICEV *or* FCV

one transition step away from each other. Table 1 contains a list of local optima in the WTW design space.

What is clear from Table 1 is that the three optima with regard to energy efficiency are quite different and thus represent truly different futures. All three local optima differ in at least three dimensions from one another. Strikingly, only one optimum was found when assessing alternative designs with regard to climate performance. This design also differs from the three optima regarding energy efficiency in at least three dimensions. We can thus conclude that the two performance measures are conflicting targets. A technological transition driven by economic performance would therefore look very different from a transition driven by climate performance.

4.3 Flexibility results

The three flexibility measures we distinguished in the previous section refer to the flexibility of an initial transition step. The possible initial transition steps are derived by checking which transition steps would not decrease either efficiency fitness or climate fitness starting from the current system being crude oil, no CCS, large, centralized truck distribution (LCT), gasoline fuel and internal combustion engine. In the economic fitness landscape, there is a choice between four initial transition steps:

- changing the distribution system into a large, centralized pipeline system (LCP)
- changing the dominant fuel into diesel
- changing the vehicle technology into a hybrid vehicle (hybrid-ICEV)
- changing the vehicle technology into a fuel cell vehicle (FCV)

In the climate fitness landscape, there is a choice between seven initial steps:

- introducing carbon capture and sequestration (CCS)
- changing the distribution system into a large, centralized pipeline system (LCP)
- changing the dominant fuel into diesel
- changing the dominant fuel into liquefied petroleum gas (LH_2)

Table 2 Design flexibility of optima

First transition step	Design flexibility			
	Global optimum efficiency	Local optimum A efficiency	Local optimum B efficiency	Global optimum environment
Transition to CCS				
Transition to LCP			*out of reach[a]*	
Transition to Diesel				
Transition to LH$_2$				
Transition to CGH$_2$				
Transition to Hybrid-ICEV				
Transition to FCV				

[a]This optimum can be reached, but not within five steps as required

- changing the dominant fuel into compressed gaseous hydrogen (CGH$_2$)
- changing the vehicle technology into a hybrid vehicle (hybrid-ICEV)
- changing the vehicle technology into a fuel cell vehicle (FCV)

Note that the four initial transition steps that are acceptable in the economic fitness landscape are also acceptable in the climate fitness landscape. We thus have seven possible initial transition steps.

We compute the flexibility measures regarding each of the seven possible initial transition steps. In the computations, we take into account only those transition paths towards optima that are not greater than five steps, including the initial step. We thus assume that transition paths involving more than five transition steps are beyond the relevant time horizon of society.

The first type of flexibility distinguished above, called *design flexibility*, we define as the number of different optima that can be reached after the initial transition step has taken place. With regard to the climate fitness landscape, this form of flexibility is irrelevant because only one optimum is present in the climate fitness landscape. With regard to the economic fitness landscape, Table 2 shows that all four possible initial transition steps remain flexible with regard to all three optima. However, a transition step to LCP excludes the possibility to reach local optimum B because such a path requires more than the maximum five transition steps we have imposed.

The second flexibility measure called *path flexibility* counts the number of different paths that lead to an optimum given the initial transition step and given the restriction of a maximum path length of five transition steps. These results are given in Table 3. First, we observe that the global optima can be reached via many more paths than the local optima. This can be interpreted as an indication that chances of a lock-in in a sub-optimal system due to current decisions are rather low.[6] Second, we observe striking differences for path

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[6]This outcome is not surprising because it is known from simulations of the NK-model that the size of the 'basin of attraction' of an optimum is positively related to the fitness of that optimum (Kauffman 1993).

Table 3 Path flexibility of optima

First transition step	Path flexibility			
	Global optimum efficiency	Local optimum *A* efficiency	Local optimum *B* efficiency	Global optimum environment
Transition to CCS				50
Transition to LCP	11	1	Out of reach	1
Transition to Diesel	14	1	2	59
Transition to LH$_2$				47
Transition to CGH$_2$				11
Transition to Hybrid-ICEV	15	2	7	32
Transition to FCV	27	5	4	22

flexibility regarding different optima and regarding different initial transition steps. For an initial step to diesel as the dominant fuel, we even counted as many as 59 possible paths leading to the global optimum in the climate fitness landscape. Such high numbers are related to the rounding of fitness values as mentioned above. Rounding creates fitness plateaus which can be traversed via many different routes.

In order to get more insight in the relevant path flexibility of each initial transition step, we repeated the exercise on path flexibility, taking into account only the shortest path. Table 4 shows that the path flexibility drastically decreases if only shortest paths are counted. Both for global and local optima, it holds that often only one possible path exists to reach the particular design. One can also observe that the shortest paths to the global optima are generally shorter than the shortest paths to local optima.

Finally, we assess each transition step on the basis of *preference flexibility*. All initial transition steps towards an optimum in the economic fitness landscape are also transition steps towards the global optimum in the climate fitness landscape. However, the reverse is not the case, as three out of seven initial transition steps towards the climate optimum do not lie on a path towards an energy efficiency optimum. If a decision-maker would only prefer emission reductions, a switch to CCS or a switch to CGH$_2$ or a switch to LH$_2$ would directly imply a significant decrease in energy efficiency. In that case,

Table 4 Path flexibility of optima for shortest paths only

First transition step	Path flexibility (shortest paths only)			
	Global optimum efficiency	Local optimum *A* efficiency	Local optimum *B* efficiency	Global optimum environment
Transition to CCS				1 (3 steps)
Transition to LCP	1 (4 steps)	1 (5 steps)	*out of reach*	1 (5 steps)
Transition to Diesel	1 (3 steps)	1 (5 steps)	2 (5 steps)	6 (4 steps)
Transition to LH$_2$				2 (4 steps)
Transition to CGH$_2$				1 (3 steps)
Transition to Hybrid-ICEV	3 (3 steps)	2 (5 steps)	1 (4 steps)	3 (4 steps)
Transition to FCV	1 (2 steps)	1 (4 steps)	4 (5 steps)	3 (4 steps)

Length of shortest path between brackets

these choices have a regret potential. A future change in preference towards reducing energy requirements may well undo these steps, thus wasting time and resources. The remaining four initial transition steps are flexible with regard to a change in preferences. From Table 4, it can further be observed that the shortest paths to the global optimum regarding climate performance (taking an initial step to either CCS or CGH_2) would come at the cost of lowering energy efficiency. Thus, the fastest route to the climate optimum is incompatible with energy efficiency improvement.

If one considers the results on the three flexibility measures jointly, some initial transition steps seem more desirable than others. The three initial steps that do not lie on a path towards an energy efficiency optimum (initial steps to CCS, LH_2 or CGH_2) are undesirable, as energy efficiency would decrease. Out of the four remaining options, changes in the vehicle technology towards either a hybrid car or a fuel cell car seem most desirable because of their combined scores on design flexibility and path flexibility.

5 Summary and conclusions

We presented a methodology to transition management that focuses on the transition path instead of the end state of a transition. More specifically, we used a complex systems approach to analyze the desirability of potential initial transition steps, given that technical evidence and social preferences may change in the future. The approach we proposed is a general approach that can be applied to any complex technology for which data on fitness values is available.

Applying the framework to data on economic and climate performance of alternative car systems, we found that *design flexibility* is high for all initial transition steps in that optima can still be reached after the initial step. Regarding *path flexibility*, defined as the number of different paths leading to an optimum, we found considerable differences across initial transition steps. Another finding was that global optima can be reached via many more paths than local optima, which reduces the chances of a lock-in into a system that is considered sub-optimal at present. Finally, we found that all initial steps acceptable in the energy efficiency landscape are also acceptable in the climate fitness landscape without the reverse being true. This renders initial transition steps robust for a change in preference from energy efficiency to environment. However, *vice versa*, not all initial transition steps were found to be robust for a change in preference from climate to energy efficiency. In addition to efficiency and climate fitness, the proposed methodology makes it possible to assess possible transition steps with respect to other possible fitness measures as well given the availability of sufficiently detailed performance data.

Overall, we conclude that changes in the vehicle technology towards either a hybrid car or a fuel cell car are most desirable because these are flexible in all respects. However, it should be borne in mind that the empirical application in first instance served an illustrative purpose. The conclusions that can be

derived from the exercise should be treated cautiously, because of the lack of precise technical data for this particular case (Schwoon 2006).

The proposed methodology can be extended to contexts where alternative search strategies apply. Instead of myopic search involving changes in a single subsystem only, larger search distances—involving changes in multiple subsystems simultaneously—apply in many technology contexts (Auerswald et al. 2000; Kauffman et al. 2000). Such an extension may well yield different results for our flexibility measures, yet without changing their meaning in any fundamental sense.

The case study illustrated that the methodology developed in this paper can lead to useful insights regarding optimal transition strategies. Taking into account future uncertainty and the flexibility of transition steps leads to more robust transition strategies, improving the chances of completing a desired transition. The methodology we proposed is complementary to alternative decision-theoretic approaches, such as real option theory, which are based on more stringent assumptions about agents' computational power and the information available to them (Trigeorgis 1996). Furthermore, our prospective approach can supplement other empirical methodologies in the field of transition management (Kemp 1994; Geels 2002; Hekkert et al. 2007; Markard and Truffer 2008) as well as simulation models on technological transitions (Windrum and Birchenhall 2005; Van den Bergh 2007; Faber and Frenken 2009; Struben and Sterman 2008).

Appendix

A fitness landscape can be represented by a graph $D = (V, A)$ that consists of a set of nodes V (the design space) and a set of directed arcs A between neighboring states x and y (the transition steps). For each pair of neighboring states, we have a directed arc $a(x, y) \in A$, where $a(x, y) = x \rightarrow y$ if $f(y) \geq f(x)$. The set of arcs is given by:

$$A = \{(x \rightarrow y)\} : (f(y) \geq f(x)) \wedge (x, y \in V)$$

where f represents the fitness function.

The optima in the fitness landscape can be described as follows:

Global optimum: $x \in V$ $s.t.$ $\neg \exists y \in V : f(y) > f(x)$
Local optimum: $x \in V$ $s.t.$ $\neg \exists y \in V : (f(y) > f(x)) \wedge (a(x, y) \in A)$

Note that each global optimum is thus also a local optimum. The design flexibility of an initial transition step is then defined by the number of different local optima in $O \subset V$ that can be reached within a certain number of later transition steps. This design flexibility F^d given an initial transition step $a(x_0, x_1)$ is then given by:

$$F^{\mathrm{d}} = |R \subset O| : \{(x_n \in O) \wedge (\{x_0, x_1, \ldots, x_n\} \subset O)$$
$$\wedge (\{a(x_o, x_1), a(x_1, x_2), \ldots, a(x_{n-1}, x_n)\} \subset A)\}$$

Where n is total number of steps in a transition path. In our computations, we used a maximum allowed path length of $n = 5$.

The second measure of flexibility describes the number of different paths that lead to a local optimum x_n. This flexibility with regard to the number of paths F^p given an initial step $a(x_0, x_1)$ and leading to local optimum x_n is then defined by:

$$F^{\mathrm{p}} = |P \subset A| : \{(\{x_0, x_1, \ldots x_n\} \subset V)$$
$$\wedge (\{a(x_0, x_1), a(x_1, x_2), \ldots, a(x_{n-1}, x_n)\} \subset A)\}$$

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