Abstract: Technological transitions generally involve multiple transition steps. Due to path dependence, an initial transition step may cut off other possible development trajectories, which later may turn out to be more desirable. For this reason, 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 the NK-model of rugged fitness landscapes that identifies the flexibility of initial transition. We illustrate our methodology by an empirical application to possible future car systems.

JEL - codes: O32, O33, B52
A complex systems methodology to transition management

Abstract: There is a general sense of urgency that major technological transitions are required for sustainable development. Yet, top-down steering of such transitions towards some pre-specified desired end state is difficult, if not impossible. Instead, transitions are best perceived as involving multiple transition steps. Due to path dependence, an initial transition step that is motivated by the wish to end up in a particular preferred system, may cut off other possible development trajectories, which later may turn out to be more desirable. For this reason, 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 that identifies the flexibility of initial transition steps from a complex systems perspective. Using the NK-model of rugged fitness landscapes, we can identify multiple local optima and characterize the flexibility of the routes towards these optima. We illustrate our methodology by an empirical application to possible future car systems.

Keywords: NK-model, flexibility, transition management, sustainable development
1. Introduction

Studies on technological transitions focus on the desirability of alternative technological options. In such a technology assessment perspective the actual transition strategy to be followed is dictated by the preferred future system. This traditional approach to technological transitions faces two problems. First, the future performance of alternative technological systems is often very uncertain. To base a transition policy on unreliable evidence possibly may well lead a society into undesirable directions. Second, given the complexity of technological systems, initial steps towards a particular preferred system may cut off other trajectories of development, which may turn out to be more desirable at a future moment in time. The first transition step can thus be decisive in steering the system as a whole into an irreversible transition process. This means that if new information becomes available regarding the desirability of technological systems, it is hard to re-orient the process of technological transitions into a new direction.

Forecasting committees and policymakers are thus faced with the problem of deciding which initial transition steps to take given that information is uncertain and initial steps can create irreversible and possibly undesirable dynamics. To take into account uncertainty and path dependence in technological development processes (David, 1985; Arthur, 1989; Cowan, 1990), we propose a complex systems approach based on the NK-model of rugged fitness landscapes (Kauffman, 1993; Frenken, 2006). This model allows us to analyze the desirability of potential initial transition steps given that the performance of future technological options is uncertain and technological transitions towards these options are path dependent sequences of transition steps.

In the following, flexibility here is defined in two ways. First, initial steps should be robust in the case of changing engineering evidence regarding the functionality (or ‘fitness’) of different technology options. Changing evidence can be dealt with by maximizing the number of local optima that can still be reached after an initial transition step as well as by maximizing the number of routes that are available to reach local optima. Second, initial transition steps should be robust to changing preferences to avoid a waste of resources by changing a subsystem and reversing the change at a later stage. In our approach, changing preferences can be dealt by pursuing transition steps that yield fitness improvements for any preference set (Pareto improvements).

We will proceed as follows. Section 2 describes the complex systems perspective of rugged fitness landscapes. Section 3 introduces the two notions of flexibility regarding initial transition steps. Section 4 illustrates the proposed methodology by applying it to the case of the transition towards a sustainable car systems. Finally, section 5 concludes.

2. NK Fitness landscapes

Complex technological systems contain several interdependent subsystems (Rosenberg, 1969; Simon, 1969; Hughes, 1983; Vincenti, 1990) that function in a coherent manner. Interdependencies between subsystems render the performance or fitness of the overall
system dependent on the 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 even for a small number of subsystems, the number of possible systems that can be assembled is large. For example, a system of size \( N=10 \), each of which can be designed in two ways, has a design space of \( 2^{10} = 1024 \) possible designs. An innovation involving a change in one or more subsystems can be represented as a move in design space from one design \( s \) to another design \( s' \).

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 most innovations indeed arise through the combination of already existing subsystems. Examples are airplanes (Bradshaw, 1992), wireless telecommunications (Levinthal, 1998) and the development of steam engines (Frenken and Nuvolari, 2004). These evolutionary dynamics are well captured by the combinatorial nature of a design space and by having innovations be represented as moves in this design space.

Complex systems theory provides us with models to study the effects of interdependencies among subsystems within systems on the search processes taking place within a design space. One influential model is the NK-model (Kauffman, 1993). The complexity of a system with \( N \) subsystems is indicated by \( K \) that refers to the number of dependency relations within the system. 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 this latter case the fitness of each subsystem is thus possibly different for different combinations of the other subsystems. Real-world systems will be characterized by a \( K \)-value in between the minimum and maximum (Simon, 2002; Frenken, 2006).

Since the fitness of a design \( s \) is dependent on the specific combination of subsystems, the fitness of a system has to be derived from the fitness of its subsystems. Without loss of generality, one can assume that fitness \( f \) of design \( s \) is described by the mean of the fitness of the subsystems (Kauffman, 1993). 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.

Interdependencies between the functioning of subsystems imply that the fitness of a particular subsystem is not fixed but dependent on the choice of other subsystems. For example, the functionality of a particular type of engine in an airplane depends on the wing design, nose design and type of materials used in the aircraft. In the example in Figure 1, 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 dependent on the choice of design for the other subsystems.

---

1 For a review of NK-models in the context of complexity theory, see Frenken (2006).
Having specified a design space and the corresponding fitness values (the ‘fitness landscape’), one can understand technological change as a move from one design \( s \) to a new design \( s' \) in the design space. We make two assumptions. First, we assume that only one subsystem is allowed to change at each time step, which means that each innovation can be represented as a move along one of the \( N \) axes of the design space. The assumption that technological transitions consists of a series of changes in subsystems is supported by the observation that, at least for large technological systems, a change in one subsystem is already 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 increases the fitness \( f \) of a technological system, hence, the metaphor of ‘hill-climbing’ (Kauffman, 1993). This assumption is supported by the idea that, since a change in one subsystem is already very costly and time-consuming, one can expect any change to be socially acceptable only if it increases the fitness of the system (thus excluding the strategy of ‘one step back, two steps forward’). In the following, we will call each innovation in a single subsystem a transition step and a series of transition steps a transition path.

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 state 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. For both types of optima, it thus holds that any further transition step in any subsystem leads to a decline in performance. In Figure 1, state 100 is a global optimum and state 111 is a local optimum. For both states it is not possible to improve fitness by moving to one of its three neighboring states.

Once a series of innovations ends up in local optimum 111, it has become impossible to make the transition to the global optimum 100. A series of innovations involved in a technological transition may thus well lead to ‘lock-in’ in a local optimum. A transition towards a local optimum is irreversible, as any move away from a local optimum would imply a decrease in performance. This means that the whole transition process is characterized by path dependence. For example, if the first transition step is 010→011, the highest gain in fitness can be achieved (from 0.2 to 0.6). Yet, the only remaining transition step from 011 is 011→111, which would thus lock-in in the local optimum. An alternative transition path involves a first transition step 010→110. Even though the gain in fitness is less than in the previous case (from 0.2 to 0.5), both the global optimum 100 and the local optimum 111 are still reachable from 110 in one further transition step. The next step would then be 110→100, which leads to the global optimum with a fitness superior to that of the local optimum. A myopic search process is thus path dependent in the sense that early decisions determine the scope of future decisions.

---

2 Formally, this representation is equivalent to mutation in biological organisms, which involves a move from one genetic string to another string in genotype space (Kauffman, 1993).
Figure 1 also shows that there can be multiple routes to the same optimum. In the example, the local optimum can be reached in four ways: via 010→011→111, via 010→110→111, via the detour 010→000→001→101→111 and via the detour 010→000→001→011→111. And, the global optimum can be reached in three ways: via 010→110→100, via 010→000→100 and via the detour 010→000→001→101→100. Fitness landscapes for larger design spaces will thus typically be characterized by a labyrinth of possible uphill routes towards optima, a property that we will explore below.

3. Flexibility in technological transitions

We will now use the properties of fitness landscapes to derive four flexibility measures that can be used to assess the desirability of the first transition step while taking into account future uncertainties. The first three 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 be false. History is full of examples in which commonly held expectations regarding future technological progress turned out to be plain wrong.3

The flexibility of a first transition step can thus 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 changing evidence is evidence that 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 to reorient the search process towards another optimum. Consider again Figure 1. If the first transition step is 010→011 the only remaining transition step from 011 is 011→111. This means that if new evidence becomes available after the first transition step that design 111 actually has zero fitness, the transition process remains stuck at 011. An alternative transition path towards 111 involves as a first transition step 010→110. At 110 both the global optimum 100 and the local optimum 111 are still reachable from 110 in one further transition step. If now evidence becomes available that the global optimum 100 actually has a fitness that is lower than the current fitness of design 110, the transition path can still be reoriented towards design 111, which now has become the global optimum. We can thus define flexibility according 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.

If changing evidence concerns designs that do not correspond to optima, but lie on a

---

3 To give one example of a completely wrong prediction has been the commonly held prediction that in post-war U.S. every household would soon have a family helicopter (Taylor 1995: 164)
transition path towards a local optimum, the transition path towards an optimum can become blocked. This is implied by the assumption that an innovation is only accepted if it increases 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 routes towards an optimum. The number of alternative routes towards an optimum can thus be considered a flexibility measure. Our second flexibility measure thus simply counts the number of different paths that lead to an optimum given an initial transition step, a measure we call path flexibility.

A third flexibility measure regarding changing evidence concerns the number of transition steps involved in a transition path starting from an initial transition step. Let the length of any transition path be defined as the number of transition steps involved in the transition path. One can reasonably assume that the changing evidence can concern any possible design s with equal probability. Therefore, short transition paths involving few intermediate transition steps are preferable to longer transition paths involving many intermediate transition steps. A third type of flexibility regarding an initial transition step is then defined as the length of the shortest transition path stemming from an initial transition step, a measure we will call time flexibility.

The fourth and final flexibility measure is not based on uncertainty due to changing evidence but on uncertainty caused by changing preferences of the decision-maker. 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 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. In Figure 2 an alternative set of preferences is presented for the same design space as in Figure 1.

<Insert Figure 2 around here>

We can now define a flexible 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 at the same time.\(^4\) Thus, if the initial transition step is described as \(s \rightarrow s'\), a flexible strategy is one for which holds that both \(f(s') \geq f(s)\) and \(g(s') \geq g(s)\). One could call this strategy a

---

\(^4\) In the example of Figure 1 and Figure 2 such a strategy would lead to the path: 010→011. From 011 there is no further win-win step possible and the end point of this transition path is state 011 that is not a (local) optimum given any of the two fitness functions. Trying to satisfy all preferences at the same time in all transition steps is thus flexible in that an initial transition step will not be undone after preferences have changed. Flexible initial steps allow for a later change in preferences and are thus preferable since they leave open the option to move on to a different transition path in the future. Yet, flexibility possibly comes at a cost because the requirement to satisfy multiple preferences halts technological development that is considered an improvement for one social group yet decrease fitness for another social group.
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) this will not lead the decision-maker to undo the initial transition step thus avoiding a waste of resources. We call this type of flexibility of the initial transition step preference flexibility.

4. The transition towards a sustainable transport system

In the remainder we will apply the four flexibility measures to data on fitness of alternative future car systems. A future transition from the current oil-based individual transportation system to a more sustainable system meets well our assumptions underlying the framework just described:

- Complexity: the system is complex in that in consist 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 expensive 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 requirement as a proxy of its economic performance and one fitness value reflecting the reduction in greenhouse gas (GHG) emissions as a proxy for its environmental performance. We assume there are two dominant social groups with different preferences, one group favoring the reduction of energy requirements of cars (efficiency) and another group favoring the reduction of GHG emissions (environment). For both fitness criteria, we can derive the global and local optima. Then, we then compute for each initial transition step that is fitness improving, the four flexibility measures. From the results, we finally draw conclusions regarding the desirability of alternative transition steps.

4.1 Design space

Technology assessment studies regarding future systems generally use a well to wheel perspective to describe alternative technological systems in terms of its subsystems. We

5 Alternatively, a Hicks-Kaldor improvement in welfare economics is a weaker restriction because it allows for choices that lead to welfare gains for one group as long as these outweigh the welfare losses for another group, so that the losses can be compensated by the gains. Note that this criterion can only be used if welfare gains and losses are all monetary, so that gains and losses can be compared.
used data from existing 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 within 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), the car fuel (nine options) and finally the vehicle type (three options). The well to wheel system including all options per subsystem is shown in Figure 3.

<Insert Figure 3 around here>

What is striking is that even for this high level of aggregation with only five subsystems, there are already $7 \times 7 \times 9 \times 3 = 2646$ theoretical combinations of energy sources, CCS, distribution systems, fuels and vehicles. The combinations form the design space of future cars. 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.

4.2 Fitness landscapes

We assessed the fitness (or performance) of each WTW system in two dimensions reflecting two preferences: WTW energy requirement per km driven (“right-wing preference”) and WTW GHG emissions per km driven (“left-wing preference”). The first we call efficiency fitness and the second environmental fitness. The two fitness values of each possible technological system are taken from a previous study by Schwoon et al. (2006), which in turn is based on the most recent WTW analyses available (GM et al., 2002; Ahlvik and Brandberg, 2001; EC-JRC, 2006).

Only a minority of 987 out of the 2646 designs were fitness improving with respect to the dominant design in terms of one or both fitness criteria. To find the local optima we checked which designs could not be improved by a change in a single subsystem regarding efficiency fitness or environmental fitness. As the fitness values were rounded to integers, chains with identical performance occur. Thus, optima can consist of more than one chain, which are ‘neighbors’ in the sense that they are no more than one transition step away from each other. Recall that one transition step involves one change in only one of the subsystems. We refer to the number of neighboring chains within an optimum as the size of a local optimum. Table 1 contains a full list of local optima in the WTW design space.

<Insert Table 1 around here>

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 environmental performance. This design also differs with 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 energy requirements would therefore look very different from a transition driven by GHG emissions.

4.2 Flexibility results

The four flexibility measures we distinguished in section 3 refer to the flexibility of an initial transition step. The possible initial transition steps are derived by checking which transition steps would increase either efficiency fitness or environmental fitness starting from the current system being crude oil, no CCS, large, centralized truck distribution (LCT), gasoline fuel and internal combustion engine. In the efficiency 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 car (hybrid-ICEV)
- changing the vehicle technology into a fuel cell car (FCV)

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

- introducing carbon capture and sequestration (CCS)
- changing from centralized truck distribution (LCT) system to a large, centralized pipeline (LCP) system
- changing from gasoline to (synthetic) diesel
- changing from gasoline to liquefied petroleum gas (LH₂)
- changing from gasoline to compressed gaseous hydrogen (CGH₂)
- changing from internal combustion engine vehicle (ICEV) to hybrid vehicle (hybrid-ICEV)
- changing from internal combustion engine vehicle (ICEV) to a fuel cell car (FCV)

Note that all initial transition steps towards a energy efficiency optimum are also transition steps towards the optimum with regard to GHG emissions, but not vice versa.

<Insert Table 2 around here>

The first type of flexibility distinguished above, called goal flexibility, we defined as the number of different optima that can be reached after the initial transition step has taken place. With regard to the reduction of GHG emissions, this form of flexibility is irrelevant because only one optimum is present in the fitness landscape. With regard to the reduction of energy requirement, it turns out that all four initial transition steps remain flexible with regard to all three optima. This means that whatever initial step is taken, all optima are still within reach.

The second flexibility measure called path flexibility counts the number of different paths that lead to an optimum given the initial transition step. We computed path flexibility of each initial transition step as the number of paths that lead to an optimum for transitions,
which are not longer than five steps. We imposed this time restriction because a transition path involving five transition steps would already imply a time horizon of some 25-50 years, given that one step generally takes 5-10 years. This is why we do not further investigate the transition step towards LCP as part of the transition path towards local optimum B, because the length of this transition path exceeds five steps. We observe striking differences for path flexibility between different initial steps and with regard to different optima. This is partly related to the fact that the fitness of some neighboring designs is the same (due to rounding), which allows one to go back and forth. Interestingly, it is clear that the global optima can be reached via many more routes than 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.\(^6\)

The third type of flexibility called \textit{time flexibility} we defined as the length of the shortest transition path stemming from an initial transition step. The shortest path towards an optimum is changing towards FCV, which requires just one more step to reach the global optimum (changing the fuel to CGH\(_2\)). This does not suggest that this transition path is most desirable, because it does not minimize GHG emissions. Most other transitions are four or five steps involving a substantial risk of ‘bad surprises’ along the way. One transition path even takes six steps.

Finally, we assess each transition step on \textit{preference flexibility}. We can readily see that four out of the seven initial steps are flexible with regard to a change in preferences in that they increase fitness both with regard to energy efficiency and with regard to environmental performance in terms of a reduction in GHG emissions. 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 respect, these choices have a regret potential. A future change in preference towards reducing energy requirements may well undo these steps thus wasting a substantial amount of resources.

To sum up, the optimal initial switch depends on the relative importance of preferences and how important different forms of flexibility are judged. Overall, it seems that changes in the vehicle technology towards either a hybrid car or a fuel cell car are most desirable because it is fairly flexible in all the four flexibility dimensions discussed.

\section*{4. Summary and conclusions}

In this paper we have presented a methodology that focuses on the transition path instead of the end states of a transition. More specifically, we use 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.

\footnote{\(^6\)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).}
Applying the framework to data on efficiency and environmental fitness of alternative car systems, we obtain insight in the flexibility of initial transition steps. We found that goal flexibility was equally high for all steps in that after the initial transition step are optima are still reachable. The path flexibility, the number of different paths that lead to an optimum, was very different for different steps. We found that global optima can be reached via many more routes than local optima, which reduce the chances of a lock-in in a sub-optimal system. We also found differences in time flexibility in that the shortest transition path stemming from an initial transition step ranges between two and six steps. Finally, we found that all initial steps improving efficiency also improve environmental fitness, which renders initial steps robust for a change in preference from efficiency to environment flexibility is high. The reverse, however, is not the case. Overall, it seems that changes in the vehicle technology towards either a hybrid car or a fuel cell car is most desirable because it is fairly flexible is all the four flexibility dimensions discussed.

This case study shows 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, ultimately improving the changes of completing the desired transition. Our prospective approach can supplement existing insights on transition management derived from case studies of historical and more recent technological transitions (Kemp, 1994; Geels, 2005; Hekkert et al., 2006).

References


Pinch, T., Bijker, W.E., 1984. The social construction of facts and artifacts: or how the sociology of science and the sociology of technology might benefit each other, Social Studies of Science 14, 399-441.


List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBG</td>
<td>Compressed biogas</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon capture and sequestration</td>
</tr>
<tr>
<td>CGH₂</td>
<td>Compressed gaseous hydrogen</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed natural gas</td>
</tr>
<tr>
<td>DME</td>
<td>Dimethyl ether</td>
</tr>
<tr>
<td>FCV</td>
<td>Fuel cell vehicle</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>ICEV</td>
<td>Internal combustion engine vehicle</td>
</tr>
<tr>
<td>LCG</td>
<td>Well-to-tank system: Large, centralized, gas-pipeline</td>
</tr>
<tr>
<td>LCP</td>
<td>Well-to-tank system: Large, centralized, pipeline</td>
</tr>
<tr>
<td>LCT</td>
<td>Well-to-tank system: Large, centralized, truck</td>
</tr>
<tr>
<td>LH₂</td>
<td>Liquified hydrogen</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquified petroleum gas</td>
</tr>
<tr>
<td>MLG</td>
<td>Well-to-tank system: Medium, local, gas-pipeline</td>
</tr>
<tr>
<td>MLP</td>
<td>Well-to-tank system: Medium, local, pipeline</td>
</tr>
<tr>
<td>MLT</td>
<td>Well-to-tank system: Medium, local, truck</td>
</tr>
<tr>
<td>NG</td>
<td>Natural gas</td>
</tr>
<tr>
<td>SO</td>
<td>WTT system: Small, on-site</td>
</tr>
<tr>
<td>WTT</td>
<td>Well-to-tank</td>
</tr>
<tr>
<td>WTW</td>
<td>Well-to-wheel</td>
</tr>
</tbody>
</table>
Figure 1: a design space with $N=3$, $K=2$ and fitness function $f$
Figure 2: an alternative fitness function $g$
Figure 3: Subsystems of the WTW system
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

Table 1: Optima of WTW systems

<table>
<thead>
<tr>
<th>First transition step</th>
<th>Path flexibility</th>
<th>Time flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First transition step</strong></td>
<td><strong>Global optimum efficiency</strong></td>
<td><strong>Local optimum A efficiency</strong></td>
</tr>
<tr>
<td>Transition to CCS</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>Transition to LCP</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Transition to Diesel</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>Transition to LH2</td>
<td>47</td>
<td>3</td>
</tr>
<tr>
<td>Transition to CGH2</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Transition to Hybrid-ICEV</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>Transition to FCV</td>
<td>27</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2: flexibility of optima