# Formalising the operation of a system innovation: A case study

Jurriaan L. Coomans
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*Abstract*—**Developing and deploying large scale system innovations can contribute to desired transitions. The preliminary step of designing these system innovations is however problematic due to the limited control over the use of the innovation over time. Studying the operation of considered designs of a system innovation could contribute to the delineation of the design space, but coverage on the operation of system innovation is lacking in the body of transition literature. This article reports on the application of a theory from the body of transition literature on a system innovation design case and the subsequent required additions to this theory to be fit for purpose. The selected theory is the Actor Option framework which refrains from aggregating system elements into regimes and niches. The additions required for the theory to be applicable are identifying the as-is dynamic of the system, the definition of a time period of interest, the selection of a time step and the definition of relevant key performance indicators.**

***Key words: System innovations, Car as a Power Plant, Actor Option Framework, System operation***

## 1. Introduction

In the face of climate change the need to contributing to the transition towards a sustainable world becomes larger. Also the TU Delft contributes to this goal by among others the Green Village initiative. The Green Village focuses on societal challenges and as a consequence looks towards technical solutions on a societal scale (van Wijk, 2013). The types of solutions the Green Village is studying are system innovations as we will define below. Designing such systems is problematic due to the characteristics of the innovations themselves and the systems they are to be embedded in. This article reports on an effort to aid in the delineation of the design space of one of the system innovations as studied by the Green Village and formulates lessons learned from this effort.

**Defining system innovations.** No single widely accepted definition of an innovation exists (Twomey & Gaziulusoy, 2014), let alone of system innovations. In this article we adopt the view as presented by Klein and Sorra (1996, p. 1057); an innovation is a new product, service, technology or practice. When we use the word innovation we do not refer a type of process which has the goal to realising novelties.

Now we have given our definition of innovations, we can use the definition of Rotmans (2005) to describe system innovations; "System innovations are organization-transcending innovations that drastically alter the relationship between the companies, organisations and individuals involved in the system. Transitions arise from a number of congregating system innovations."

**Designing system innovations.** The system innovations as studied by the Green Village are designed to have societal impact and to change infrastructure systems. The infrastructure systems are complex systems characterised by distributed control. As a consequence these systems cannot be engineered by one actor but instead evolve as a result of the (inter)actions of all involved actors, where each actor can only partially influence the path of the system over time (Chappin, 2011). The actor that is to design a system innovation that is to be embedded in an infrastructure system will only have limited control over the way these artefacts will actually be used in time. How can we then come to a design that is most likely going to be adopted and operated according our goals? The importance of the design phase is clear seeing the limited possibility to intervene in the lay-out of the physical network once the artefact is deployed. Herder, Bouwmans, Dijkema, Stikkelman, and Weijnen (2008) summarise this dilemma by pointing towards the contradiction in terms of complex system design: "Complex systems evolve and have fluid boundaries, while design generally is concerned with an artefact which purpose and system boundary are both well-known and static." This makes it difficult to determine the 'solution space' for these kind of design efforts (Herder et al., 2008).

To gain insight into the boundaries of the solution space the operation of a few pre-defined chosen designs can be simulated with a computer model. By identifying which factors form major barriers for the successful operation of the virtual artefact, we can gain insight into the boundaries of the solution space of the real artefact. A challenge for such a

This is an accompanying article with the thesis "Exploring the operation of a Car Park Power Plant" written by the same author. The thesis can be downloaded from repository.tudelft.nl.

modelling study is however the step of system identification. It is difficult to establish which elements are and are not to be included in the conceptual model as the infrastructure systems are complex and connected to other infrastructure systems

**Approach.** To structure the step of system identification, some of the dominant theories from the body of transition literature are reviewed and one of these theories is selected as guiding. The application of the theory on a researched system innovation of the Green Village leads to the formulation of lessons learned on how the operation of system innovations can be studied based on the concepts of the transition literature.

**Structure.** The project that serves as a case for this research is very briefly introduced in section 2. To find guidance in the step of system identification a review of possible supporting theories has been conducted and is reported in section 3. The application of the selected theory on the used case study is the subject of section 4. Section 5 presents our findings and lessons learned based on the application of the theory on the selected case. The conclusions are presented for the used approach on the operation of system innovations in section 6.

## 2. Car Park Power Plants

One of the projects of the Green Village is the Car as a Power Plant (CaPP) project. A form the CaPP concepts is the Car Park Power Plant (CPPPs). CPPPs are parking garages in which the fuel cells of parked fuel cell vehicles are used for the generation of electricity. By including on-site hydrogen production methods, the CPPPs are expected to purchase electricity when it is cheap (possibly due to excess wind energy), store it, and convert it back to electricity when the electricity price is high. The major systems that would be affected by the large scale introduction of the CPPPs are the person transport system and the electricity system. As both are infrastructure systems the design challenges as described earlier apply. A more detailed discussion of the CaPP and CPPP concepts can be found in (van Wijk & Verhoef, 2014) and the accompanying thesis.

For the case study we set ourselves the goal to identify possible factors that could form barriers for the successful operation of a CPPP. The underlying rationale is that if our approach by using the selected transition theory to identify these barriers, it is fit for the purpose of formalisation of the operation of system innovations.

## 3. Transition literature

For our purposes we structure our literature discussion by first discussing the relatively older descriptive theories. Subsequently the explanatory theories are discussed.

### A. *Descriptive theories*

**MLP** The dominant theory in the body of transition literature is the Multi-level perspective (MLP) (Yücel, 2010). The core of the MLP is the regime concept at the meso level of the perspective. Regimes are 'the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems' (Geels & Kemp, 2007). Niches are the places where innovations can emerge and are at the micro level of the framework. The macro level consists of the sociotechnical landscape and can exert pressure on the current regime. If a niche innovation has gained enough momentum, landscape pressure can lead to the adoption of the niche technology, resulting in a new sociotechnical regime and the occurrence of a transition (Geels & Schot, 2007).

The MLP relies on the power of aggregation in order to construct conceptual levels and to provide a useful guiding framework (Yücel, 2010). This aggregation is however sometimes problematic, as different actors and accompanying perspective on the reality will result in a different categorisation of forces and groups. This makes the distinction of the three levels non ontological (Raven, van den Bosch, & Weterings, 2010). The MLP has often been used for historical transition cases studies (Geels & Kemp, 2007) but provides little basis for insights into the mechanisms behind a transition.

**TM** Many of the scholars who have contributed to the development of Transition Management (TM) are colleagues of the developers of the MLP. As a result much of the TM literature uses the MLP as a mean to convey ideas and frame concepts (Twomey & Gaziulusoy, 2014). The starting point of TM is a certain societal problem for which a transition path is to be developed (Loorbach & van Raak, 2006). TM does not aim to control transitions or guide them to specific outcomes, instead the direction and speed of the transition is influenced through a bottom up approach using adaptive policies (Loorbach & Rotmans, 2006). The core of TM is a set nine governance tenets which first have been used in a descriptive framework, and later in a prescriptive framework.

Compared to other transition theories, TM has been developed to offer practical insights. It is however poorly backed with empirical documentation (Loorbach & van Raak, 2006). TM is a future oriented approach that prescribes how one could influence a current undergoing transition process by managing systems during different types of activities and on different levels. TM explains why such recommendations could be effective in driving a transition process by using the concepts from the MLP (Rotmans & Loorbach, 2009). In other words the aggregation concepts of the MLP (external landscape, regime and niches) are used as the main subjects on which the narratives of TM are based. TM does not provide a description of the dynamics behind the expected effects.

**SNM** Where TM starts from a societal problem, a certain technology is the starting point for Strategic Niche Management (SNM) (Loorbach & van Raak, 2006). SNM focuses on the planned development of protected spaces for a new technology (Kemp, Rip, & Schot, 2001) through a process with the focus on experiments and learning. These experiments are settings in which the various innovation stakeholders are encouraged to collaborate and exchange information, knowledge and experience (Chappin, 2011). Through the experiments the involved actors should learn about the viability of the technology and be stimulated to build a supporting network around the product which all together should bring the technology from idea or prototype into real use (Kemp et al., 2001). SNM focusses on the micro or niche level of the MLP. It deals with how different innovations could interact and eventually penetrate the socio-technical regime via an demand-supply dynamic (Loorbach & van Raak, 2006; Twomey & Gaziulusoy, 2014).

SNM can prove useful to use as a guideline to manage and build a social network surrounding transitions. Due to its qualitative approach and dependence on the social network, SNM however gives little support to quantitative explorations.

**TIS** A technical Innovation System (TIS) is a type of innovation system. An innovation system consists of the participants or actors, their activities and interactions, as well as the socio-economic environment, which all together determine the innovative performance of the system (Eggink, 2012). The main focus of a TIS approach is to understand the success or failure of a specific technology based on the functioning of the TIS (Twomey & Gaziulusoy, 2014). A TIS has four structural components; actors, institutions, networks and technological factors (Eggink, 2013; Hekkert, Negro, Heimerinks, & Harmsen, 2011). The interaction of these components results in the functioning of the innovation system with respect to the emergence or production of innovation (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). This functioning is then tested on the fulfilment of seven functions that are deemed to be indicative for successful system functioning. Depending on the phase the TIS is in (pre-development, development, take off or acceleration) the lack of proper filling in a function may become a barrier for proper system development (Hekkert et al., 2011). By using the seven functions to evaluate the system during its different phases, policy recommendations can be made concerning the structural components.

TIS provides some different insights with respect to the MLP based theories (although IS also bases some of its concepts on the MLP) (Chappin, 2011). The core of the theory is the set of the seven system functions which have a strong evaluative character. Further work on the theory of TIS is suggested to focus on the dynamics of these systems (Hekkert et al., 2007).

*B. Explanatory theories*

**PT** Building on the foundations of the MLP de Haan (2010) formulated the Pillar Theory (PT) during his PhD in the group of the main contributors of the MLP. PT could be seen as an additional theoretical layer surrounding the MLP. The main elements in the theory are constellations. Constellations are subsystems that are providing a certain societal need within a societal system, examples of the public transport and the car based personal transport system are given by de Haan (2010). PT explains transitions as the interplay of conditions and patterns. Conditions are aspects of a societal system that make a system prone to change. Conditions lead to patterns which are ways a transitional change takes place. Patterns lead to new conditions and so the chain of events continues. Chains of patterns are called transition paths and they are the final deliverable of PT. In order to be able to focus analyses based on PT, de Haan describes and limits the theory to three types of conditions, three types of related patterns and four types of paths that could manifest themselves (de Haan, 2010).

We view PT as an additional theoretical layer of the MLP as it tried adds an explanatory dimension to the MLP; where the MLP describes what is happening, PT describes why it is happening through the use of conditions and patterns. PT resides at the abstraction level of the MLP and uses the concepts niches and regimes to build its narratives (Yücel, 2010). For the goal of PT, being to provide a generic explanation on transition dynamics (Yücel, 2010), it is sufficient to use the concept of niches and regimes as black boxes and study their dynamics. In the view of de Haan (2010) the dynamics and interactions of the constellations are by structuring them in conditions, patterns and paths explanatory for transitions. Yücel (2010) however questions if this is a full explanation. He considers PT as being more descriptive than explanatory due to the lack of postulation of behaviour rules of the conditions and patterns.

**MCF** The Matisse Conceptual Framework (MCF) originates out of the MATISSE project funded by the EU. It displays itself as a framework that is to address the challenge of modelling non-linear social dynamics of future transition to sustainability (Haxeltine et al., 2008). A main challenge for the MCF was to be able to reconstruct the transition pathways as defined by Geels and Schot (2007) (Yücel, 2010). For this challenge the MLP was adopted making niches and regimes the research objects in the MCF (Holtz, 2011). There are many similarities between MCF and PT (Holtz, 2011), which is likely caused by the fact they both originated from Geels and Schot (2007). However in the literature on MCF the link with PT and vice versa has not been discussed.

The idea behind the MCF is to model constellations (used in the same way as in PT) in a multidimensional grid called the practice space. Each dimension represents a different characteristic of the constellation under consideration, for instance carbon-intensity. Agents that reside in the practice space are regimes, niche-regimes (more power full niches),

niches and consumers. The success of the non-consumers is determined by consumers who move within the practice space. If the location of a niche or regime overlaps with that of a consumer, this consumer is automatically supporting this actor, making it more successful (Haxeltine et al., 2008; Holtz, 2011; Köhler et al., 2009). Niches and regimes have different heuristics with respect to their actions. Niches move in the practice space as long as a certain direction is increasing their support. Regimes generally maintain their position (their 'practice') and will start to move if their dominant position is under threat. Interactions between different types of agents could take the form of niches being absorbed by the regime or the regime trying to move consumers in a new direction. Depending on the amount of support or through different activities niches may be transformed into regimes or vice versa (Haxeltine et al., 2008).

Criticism on the MCF mainly focuses on the lack of argumentation on the imposed dynamics. MCF is said to use many weakly core assumptions that are expected to be the result of the intuition of the researches themselves (Holtz, 2011). Also the question of providing a satisfactory explanation rises as did when we discussed PT. Some dynamics are reproduced based on certain conditions and mechanics on the niche/regime aggregation level. However the behavioural rules of these niches and regimes themselves have not been underpinned (Yücel, 2010).

**AOF** The Actor Option Framework (AOF) aims to provide a general conceptual framework for simulation supported transition analyses (Holtz, 2011) and was constructed by Yücel (2010) during his PhD research at the TU Delft. An analysis using the AOF has its starting point at a certain societal need that has to be fulfilled. When using the framework a researcher is to identify options which are the technologies combined with the manners these technologies are used to fulfil the societal (Yücel, 2010). Actors are the main drivers of the system and determine the behaviour of a system by the choices they make related to options; they *choose* which option to support (Yücel, 2010). The decision making of actors in the AOF is based on prospect theory of Kahneman and Tversky (1979) and is split up in a framing phase (projecting alternative courses of action based on available knowledge on these courses) and a valuation phase (make decisions as a consequence of valuing this framed information) (Yücel, 2010). Actors are heterogeneous based on their decision making rules and the impact of their decisions (Yücel, 2010). This leads to the identification of four main groups to which an actor could belong: practitioners, providers, opinion groups and government (Holtz, 2011).

The interplay between actors (social agents) and options (technical agents) results in the system behaviour. In the AOF actors influence the existence of options and their properties. Based on new sets of options or option properties, actors update their information and beliefs resulting in new actions taken by the actors. The technological and social elements in the system co-evolve and result in the dynamics of the system under consideration (Holtz, 2011). The coevolution occurs through different mechanisms which are specific instances of change processes and interactions between actors and options. Mechanisms could target the way options are used, the set of available options, the options' properties, the information possessed by the actor and the identity of an actor on which the actor bases its behaviour (Yücel, 2010). Yücel has formulated a set of relatively simple mechanisms that could be seen as the first building blocks that can be used to construct the so called web of the active mechanisms in the specific case. In different cases, different sets of mechanisms are expected to be active. The internal simultaneous interaction of the active mechanisms leads to the complex dynamics that can be observed during transitions processes (Holtz, 2011; Yücel, 2010). Yücel (2010) also formulated a roadmap consisting out of seven steps in order to guide the development of a model based on the AOF.

The AOF is different from the other explanatory theories given its more detailed scope of analysis. Where PT and MCF considered niches and regimes to be the active entities, the AOF explicitly opens up these concepts and bases its analysis on the elements of the socio-technical system, making it easier to link findings from the analysis to real-world policy making (Yücel, 2010). A downside of the scope of the AOF is the need of a large amount of information for model design, validation and robustness testing (Holtz, 2011).

### *C. Position of system innovations in transition literature*

The main body of transition literature has a descriptive focus on historical completed transitions. The transitions that have been studied typically span over several decades which is thus also the typical timeframe that is used by scholars to frame these processes (Chappin, 2011; Yücel, 2010). Concerning the things that change, the literature focusses on relatively large entities usually being sectors and organisations (Chappin, 2011). If we use this perspective we would gain a focus on why these systems might or might not change over the upcoming decades and what role the system innovations *as niches* can play in these transitions. We are however interested in the operation of the system innovations themselves which occur at a more detailed, lower and finer granulated aggregation level. This level is different from the transition level which is used by the majority of the current body of transition literature.

### *D. Selection*

The dominance of the MLP in the body of literature results in many of the theories applying the aggregation level of this perspective. Yücel (2010, p. 16) uses the term structuralist stance which is explained as "relying on a (social) structure that is autonomous from the individual elements (e.g. individual person), which constitute the structure, in explaining a (social) phenomenon." By aggregating the system into the three levels of the MLP the scholars are using this structuralist stance (in among others the PT and MCF).

Subsequently they assign properties to, define actions on the basis of, and interpret results as the consequence of dynamics of the niches and regimes concepts. For the goals of the MLP, PT and MCF this is very useful in order to maintain a workable theory (Yücel, 2010). However it does not provide a basis for studies that aim to gain knowledge about processes that occur within the aggregated concepts of niches and regimes.

The alternative would be not seeing niches and regimes as black boxes, but basing an analysis on the constituents within these black boxes. The regimes and niches are no longer the protagonists, but serve as "conceptual borders" (Yücel, 2010). Such an approach looks at the different elements in more detail and could be said to be finer granulated. The AOF is an example of this latter approach and is looking inside the regime and try to understand the changes of a system at a more fine grained level. The price of using a more detailed scope is however the requirement of more input (Holtz, 2011).

Based on the insights we have gained through the literature review we select the AOF as a leading theory for our case. The theory uses a focus that allows research to be conducted at the level of processes within the concepts of niches and regimes. Furthermore Yücel (2010) provides a clear step by step approach. Lastly the set of concepts of the AOF are flexible enough to be adjusted to a specific case, but allows for comparison between models and theory building (Holtz, 2011).

The focus of the AOF is however on full transition processes which is different from our focus on the operation of System Innovations. By applying the theory to our case nevertheless, and reflect upon the use of the resulting system identification a contribution can be made to the AOF by suggesting additions to make the theory better applicable for the operation of system innovations.

## 4. CaPP case

### A. System identification: Applying the AOF

The AOF guides system identification by having the user answering a set of seven questions. In this section we will discuss the answers for each question for the CaPP case.

*1) What is the societal function/need of concern?*

The societal function of concern acts as the 'anchor concept' of the AOF. It is the starting point from which all other relevant actors, options and processes are identified.

For our study the societal function that is to be fulfilled is the demand of mobility with car usage. This demand can be split into three; having a car available, driving the car at desired times and parking the car after usage.

*2) Which aspects of the societal function characterize the transitional change?*

Not all aspects related to the societal function are of interest for the CaPP case. Defining which aspects of the societal function are of interest, allows for further narrowing the focus of the identification of relevant actors, options and interactions.

Our focus in this modelling effort is on the profitable exploitation of the potential of parked FCV's. More specifically we aim to understand which factors could form barriers for achieving viable financial performance when operating the CPPP.

*3) What are alternative means of fulfilling the societal function?*

In this step we define the different options that are considered in our model. An option is the combination of a technological artefact with its accompanying mean of using. For the car drivers we have used three types of variations in the options.

Driver: Type of owned car

First of all the type of car that is available to the driver is of concern. In the case study we considered internal combustion vehicles (ICVs) and the FCVs. For the sake of simplicity we thus have excluded future competing alternatives such as (hybrid) electric cars. We study a world in which fuel cell vehicles are widely available and used in daily life.

Driver: Parking behaviour

The second relevant variation is the location of parking the car during times it is not in use. We assume the majority of the trips to be between home and work, and subsequently the car is being parked at home or at work. During these times we are interested if the cars are being parked in a CPPP or not. This leaves us with four variations to explore.

Driver: CPPP contract specifics

Lastly the term on which the drivers agree to park their car in the CPPP can differ. For our project we include one contract element; the times of obligatory parking.

*4) Who are the major social actors in the system?*

The actors are the major players in the AOF and have the largest influence on the system behaviour through their decisions with respect to the options. The AOF distinguishes four categories in which relevant actors could be sought: users, suppliers, regulators and opinion groups. For the CaPP case we have studied the behaviour of the first two groups of users and suppliers;

Users/Practitioners

The group of actors that is utilising the options is the group of car drivers. In our case the key decisions that are being made by the users is the choice for a driving technology (ICV or FCV) and if the driver uses the services of the CPPP(s) under the offered conditions.

Suppliers

When related to the different types of options we distinguish two sets of suppliers of the options. First the cars are being provided by either car dealers or other suppliers such as leasing companies. For our purpose the origin of the cars is of little interest. This allows aggregating all the different car suppliers into one. For the sake of simplicity we let the environment sell the cars to the drivers.

The second type of supplier is the company that is operating the CPPPs and offering the CaPP service. For our delineated world of no more than several CPPPs will be in place. We assume that our limited amount of CPPPs will not compete with on another allowing us to simplify the ownership of the CPPPs to one actor.

*5) How to formalize actors' decision-making?*

Within the AOF a large role is given to the prospect theory of Tversky and Kahneman (1992). The theory prescribes splitting decision making by actors into framing and valuation. Actors frame different options according to the information they possess. The possessed information represents the beliefs of the actor and can be incomplete or incorrect.

**General procedure.** Valuation of different decision options is based on the preference structure of an actor. Such preference structure represents the importance of different aspects of the consequences of making a certain decision to the actor. The preference structure contains different dimensions which should be attempted to limited to a maximum of six for the purposes of the AOF (Yücel, 2010). The preference structure of actors could change over the course of time and could be influenced by for instance commitment forming or the adjustment of the actors' references.

If the preference structure of an actor is determined, a value function based on the beliefs of the actor is to be calculated per decision option in order to allow the actor to compare the different options with one another. The actor then chooses the option which has the highest expected utility. The preference structure of the actors in our model and the construction of a value function are discussed below.

For the CaPP case we have adopted the two choice models by Hidrue, Parsons, Kempton, and Gardner (2011) and Parsons, Hidrue, Kempton, and Gardner (2014). For these models 3029 North American participants were asked to choose between an ICV, an electric vehicle without V2G capabilities or an EV with V2G capabilities and the accompanying contract. Using this choice model is not ideal as it their focuses do not fully match ours, especially the difference between the types of cars that is considered by the participant. A more suited combination of models for the CaPP case does to our knowledge not exist.

The precise adoption of the choice models requires a description of substantial length which we will not present here. Please refer to section 5.2.5 of the accompanying thesis for this description (Coomans, 2015). In the case study two value functions are calculated; a value function on which a choice for a FCV or ICV is made, and a value function which determines if a driver will adopt a CaPP parking behaviour or not.

*6) How are the options characterized in the model?*

The AOF suggests using two classes of attributes in order to structure the mapping of relevant attributes.

The first class of attributes are those that must be included in the formalisation as they are being used by the actors to base decisions upon. The attributes used for our value functions have been adopted from Hidrue et al. (2011) and Parsons et al. (2014) and are complemented by an attribute that mimics the centralisation effect of CPPPS. The two value functions that are used in our study require the monitoring of the following attributes:

For the decision to buy an ICV or an FCV:

- Price FCV [€]
- Fuel costs FCV [€/km]
- Pollution FCV [kg CO2-eq/km]
- Price ICS [€]
- Fuel costs ICS [€/km]
- Pollution ICS [kg CO2-eq/km]

For the decision start using the services of a CPPP:

- Required plugin time [hours per day]
- Cash back [€/yr]
- The time it takes to walk from the CPPP to the destination [minutes]

Furthermore attributes that are used to make decisions upon are CPPP attributes that indicate the state of the CPPP and allow for controlling the installation:

- Available production capacity
- Available hydrogen in storage
- Expectation of required storage for the upcoming day
- Expectation of electricity prices for the upcoming day
- Expected FCV availability for the upcoming day

The other class of attributes worth monitoring are those related to the performance of the system. For our purposes we require information on the financial performance of the CPPPs and have thus monitored the following attributes:

- Cumulative system pollution
- FCV ownership percentage
- CPPP service usage percentage

*7) Which mechanisms are 'active' in the analysis context?*
The web of mechanisms is within the AOF expected to mimic the complex dynamics of socio-technical systems. A mechanism has three important aspects: every mechanism has a trigger; not all mechanisms operate at the same time-scale; the mechanism has a specific consequence. Yücel (2010) has identified a set of ten types of mechanism that can be expected in socio-technical systems. Discussion of all mechanisms goes outside the scope of this article. The mechanisms consider changes in option properties, changes in actor perceptions and changes with respect to actors' preference structures. The discussion of each mechanism and how it relates to the CaPP case can be found in section 5.2.6 in the accompanying thesis (Coomans, 2015). From this discussion one will find that a large share of the mechanisms as proposed by Yücel (2010) were found to not apply to the CaPP case. This might not come as a surprise as the mechanisms have been tailored to mimic transition dynamics and our case focuses on dynamics of the operation of a system innovation.

*B. Iteration: additions to AOF guidance*

After we have gone through the seven steps of the AOF we reflect upon the system identification and if we have obtained all required information. Following several iterations we end up with making four additions to the guidance of the AOF.

*1) As is dynamics*
The AOF focuses on transition processes which are types of change (Chappin, 2011). As our interest is on the general operation of a system innovation we find that the identification by directly following the suggestions of the AOF, lacks the inclusion of a "as-is" dynamic. This dynamic should reflect the working of the system if it is not changing. For our case study the movements of the drivers and the daily operation of the CPPP was added to the model.

*2) Time period*
Again following from the focus on changes in societal systems, the time scale of the AOF is dependent on when the transition can be said to be complete. This could be one year or several decades. Our model with its focus on the operation of a technical installation does however not have a time scale dependent on the occurrence of a certain event. As such we have defined the time scale of our model to be three years.

*3) Time step*
The AOF does not support in the definition of a relevant time step for a model. Focusing on operational performance leads to a focus on relatively detailed level of the installation and idem time scale. We have used the smallest time scale of the set of relevant processes for the operation of the installation, and as a result used a time step of 15 minutes based on the timescale some of the electricity prices are defined.

*4) KPI's*
The AOF suggests defining the aspects of the social need that would have changed after a transition to assess if a transition has taken place. For our purposes this measure is meaningless as we do not intend to specifically observe the change process. Instead we aim to gain a better understanding of the performance of the installation during the time period of three years. We have used different alternative key performance indicators of which the Return on Investment for the CPPP owner was chosen to be the major outcome of interest. For this purpose we have included additional attributes that are to be monitored. These attributes are the cumulative operational revenues and the cumulative operational cost made by the CPPP.

*C. Formalisation*

The identified system decomposition has been coded into a simulation model. For this activity we have used the approach as suggested by Van Dam, Nikolic, and Lukszo (2013). The model has been constructed as an agent based model in the programme Netlogo 5.1.0 (Wilensky, 1999). The identified system decomposition has been translated in the model structure as presented in Figure 1. For an elaborate description of the model the reader is referred to chapter 6 of the accompanying thesis (Coomans, 2015).

*D. Exploratory experimentation*

Two separate experiments and accompanying analyses were conducted with the model.

**Preliminary runs**. The preliminary runs are executed to provide a first insight into the behaviour of the model. The runs are executed by varying sixteen possible design variation of the CPPP. The focus of this experiment is on gaining a feeling of the effect of the used design on the behaviour of the model. With the aid of linear regression we have structured the simulation outcomes and found basis for more detailed analyses of specific runs and model elements.

**Sensitivity runs.** The preliminary runs are executed over a pre-defined set of environmental variables. This gave some insight into the model behaviour, but only executing the preliminary runs would provide little knowledge on how the CPPPs might perform under a different set of environmental variables. By running and analysing sensitivity runs we gains some feeling for the effect of certain factors on the behaviour of the model.

*E. Results*

From the two experiments we have successfully identified possible six factors that in sets of three form possible barriers for a successful operation of a CPPP:

The usage of simple CPPP operation tactics will result in CPPPs to produce electricity at all moments that satisfy the selected use-case. As a result the CPPP desires to produce electricity during many hours of the day.

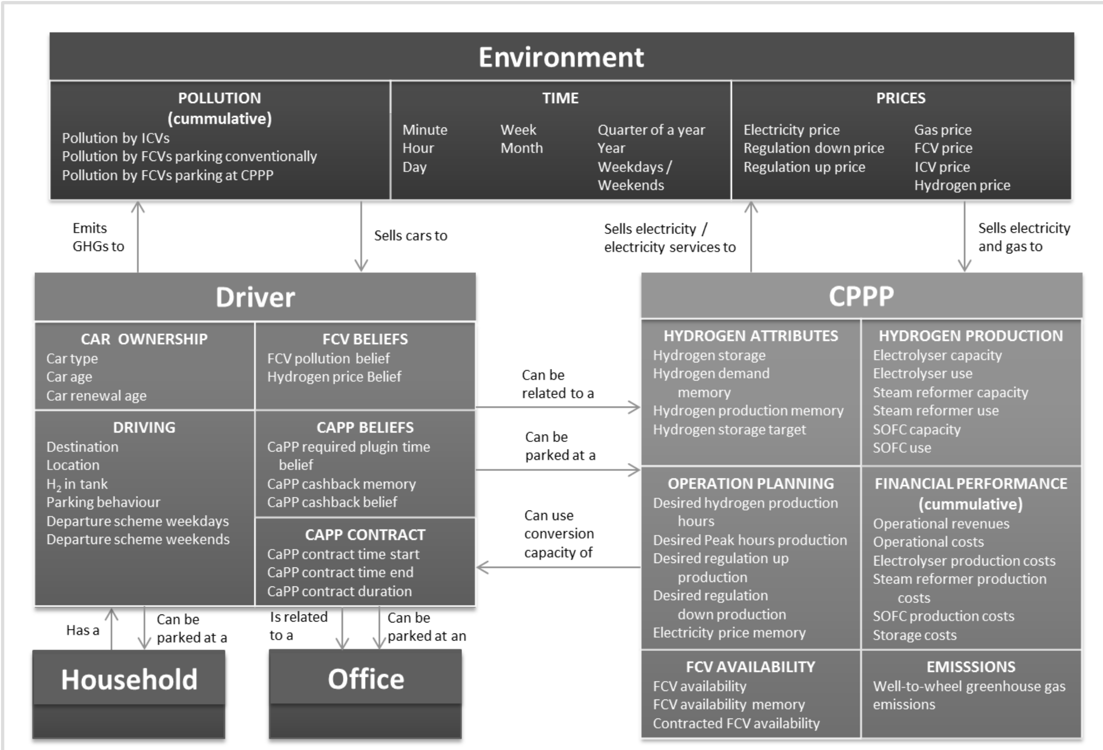


***Figure 1: Model elements, attributes and relations***

FCVs are expected to have production capacities of around 100 kW. If the conversion efficiencies of FCVs remain in the range of what they are now, the FCVs could require an amount of hydrogen per hour that comes close to the daily capacities of today's on-site hydrogen production devices. Combined with the desire to produce electricity during many hours a day, an unsatisfiable hydrogen demand and a continuous hydrogen production emerges.

Without the possibility to determine profitable hours of hydrogen production, the possibility of making use of the price differences of electricity during a day will no longer be present. As a result the value of storage becomes too small to compensate for the conversion losses within the CPPP. In these cases the CPPP can be expected to make operational losses due to the absence of a positive profit margin.

Choosing to reward drivers who park at a CPPP with a free refill of hydrogen is unlikely to have significant effects on their perceptions. Due to the fact that FCVs consume a small amount hydrogen per driven kilometre, the perceived monetary value of the received free hydrogen is insufficient to structurally persuade drivers to park at the CPPP.

Also the effect of the existence of a CPPP on the decision of driver with respect to the choice between purchasing an FCV or a conventional vehicle could be limited. Benefits that a CPPP could offer for FCV owners are a reduction in fuel costs and an improved environmental performance of their vehicle. The valuation of these benefits by drivers is however insignificant when compared to the valuation of the purchase price of vehicles.

If both the share of drivers with an FCV and the share of these drivers that park their car at a CPPP are low, the CPPP will have to rely on a very large driver population. This would make it difficult to find a suitable location that such a large base population would consider to use as a daily parking location.

## 5. Reflection upon usage of the AOF for studying the operation of system innovations

From our experience the usage of the AOF was valuable as a supportive structure to base our filtration of reality upon. The fact that we have been able to fulfil our case related objective of identifying barriers for successful CPPP operation proves that at least for the case of the Green Village the usage of the AOF has been adequate.

Our expectations are that this approach can be general applicable we would recommend other researchers interested in studying system innovations to seriously consider the framework as an aid. Before a general approach of studying system innovations with the AOF can be established some additional work will have to be executed.

First of all we have found validation of our approach to be problematic. Seeing that our approach has not been executed before and that our case concerns a future development we deal with a model that is based on two uncertainties. If a validation error would occur, we would be unable to assess if this error is caused by our understanding of reality or the method we used to represent this reality. The execution of more case studies and studies towards historical event could validate the AOF as a useful method to study system innovations and give more certainty for future studies.

A second point of improvement would be reviewing the list of basic mechanisms as used in the AOF. This list contains types of mechanisms that have been observed to be of relevance for transitions. We have observed that many of the mechanisms were deemed not to be of effect for our and this brings up the question if this list is adequate for formalising system innovations. Again, applying the AOF on historic case studies could strengthen the approach for this cause.

Lastly we were forced to make four additions to the guidelines of the AOF: the definition of a time step, the definition of a time period of interest, the definition of key performance indicators and the addition of as-is dynamics. We expect that additionally executing these steps will be relevant for any research using the AOF for studying system innovations, but more case studies should confirm this.

The addition of elements to the identified system has made our model larger. The inclusion of the as-is dynamics and other KPI's required some additional coding but did not result in large difficulties. However a drawback of our approach was found when comparing the defined time period and time step.

Including operational aspects forced us to switch to relatively small time steps, in the order of minutes. In order to still observer middle-term behaviour the model is as a result required to simulate for a long time period in the order of years. As a consequence the model analysis became a challenge as the required computational time for experiments was about one minute with the available computers. This resulted in a limited flexibility for running experiments. The relatively long simulation time also prevents the use of some alternative method of analysis difficult, as these methods rely on the execution of a very large number of runs. Additionally due to the large number of simulated time steps we were unable to log the data of every time step. This latter complication could however be solved by using other simulation languages than Netlogo.

## 6. Conclusions

For the study of the operation of a system innovation a theory from the body of transition literature was selected and applied on the Car Park Power Plant case.

From the available theories we have selected the Actor Option framework (AOF) to be the most applicable for our purposes. The main reasons for doing so was the fact that the AOF refrained from treating niches and regimes as black boxes but provides concepts that allow studying processes at more detailed levels.

The application of the AOF resulted in a system identification that laid down the basis for a model with which we successfully explored the exploration of a system innovation. Although the guidance of the AOF was experienced as very useful, four elements had to be added to the system identification in order to result in a useful model. These elements are the as-is dynamic of the system, the definition of a time period of interest, the definition of a time step and finally the definition of relevant key performance indicators.

The fact that the behaviour of interest on which the AOF focusses is different from that of ours is seen as the underlying reason why these elements were not included in the AOF.

The main drawback that was experienced from adding the elements is the large amount of time steps that is required to simulate one run. The combination of the time step of fifteen minutes and the time period of interest of three years, leads to over 100.000 time steps per simulation. As a result the time required per simulation experiment becomes large and limits the flexibility of the researcher. Also the logging of data during runs was experienced to be challenging.

Additional research into the usage of the AOF for the formalisation of the operation of system innovations is recommended. Mainly the application of the approach on historical cases could contribute to easier validation of the resulting models and a more applicable list of mechanisms that can be expected to be relevant for the case of system innovations.

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