Generic time- and method-interdependencies of empirical impact-measurements: A generalizable model of adaptation-processes of carsharing-users' mobility-behavior over time

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Abstract

The purpose of this article is to advance empirical sustainability-evaluations of carsharing-systems. Carsharing, a frequently cited example of a product–service system (PSS), is currently morphing from a niche into a mainstream mode of transportation. Carsharing has the potential to provide a more sustainable mobility-option compared to private car usage, for example by reducing the overall motor-vehicle traffic in cities. However, the quantification of this potential is complex, and few studies have analyzed the fundamental impacts of the chosen measurement-methodology on the results of empirical carsharing-evaluations. This article analyses the time- and method-interdependencies of carsharing-studies based on a generic model structuring the adaptation of the mobility-behavior of carsharing-users over time. A paradigm shift from a static to a dynamic view on impacts of the PSS carsharing is proposed, which could support policymakers enacting carsharing-regulations in cities. The analysis of generic methodological interdependencies when conceptualizing impacts as dynamic processes is generalizable to impact-assessments of new technologies changing user-behavior over time.

Keywords

Impact-measurement; Quantitative-empirical methodology; Generic model; Adaptation-process over time; Carsharing; Shared mobility

Note: The Figures are embedded within this text to avoid scrolling; a potential revision will include source files.

1. Introduction

Private cars create negative externalities. For example, air pollution in Beijing worsened as the number of motor vehicles in the city increased from 2 million in 2004 to 4.8 million in 2010 (Chen and Zhao, 2013), which led to highway closures and health warnings by the Chinese government (Harris, 2014). To put this externality into perspective: The U.S. Embassy in Beijing monitors local air conditions on a scale from *Good* to *Hazardous* (U.S. Embassy Beijing, 2014) and in January 2014, Beijing's air pollution ranked *Beyond Index* (Wong, 2014). Other negative externalities of private car usage include parking-space shortage and traffic congestion. Studies in different cities found “between 8 and 74 percent of the traffic was cruising for parking” (Shoup, 2006, p. 479).

Efficiency gains of private cars will not solve such scale-related problems. The widespread human preference for private cars leads to tragedies of the commons (Hardin, 1968) because no matter how sustainable individual private cars are designed, manufactured, and driven, the consumption-decisions of millions of private car owners all reduce the availability of limited public goods, such as clean air and public space. Thus technology improvements are insufficient for automakers to achieve sustainable business models (Williams, 2006, 2007) and “[a] fundamental rethinking of the entire system of personal mobility is necessary” (Vergragt and Brown, 2007, p. 1104). A special issue of the Journal of Cleaner Production on *The Automobile Industry & Sustainability* indicated that “the world is in desperate need of real and substantial progress in [the automobile industry]” (Orsato and Wells, 2007, p. 993)– but how can the automobile industry achieve real and substantial progress? How can individual mobility be provided more sustainably?

Shared cars offered via the product–service system (PSS) carsharing could contribute to a solution. Most PSS-classifications distinguish *product-oriented*, *use-oriented*, and *result-oriented* PSS-variants (e.g. Tukker, 2015; Williams, 2007), whereby carsharing is typically classified as a use-oriented PSS. Carsharing saves resources through two mechanisms: First, fewer cars have to be produced (in total) when people share cars driven consecutively as opposed to everyone owning a private car individually. Second, carsharing encourages low-car-usage lifestyles as the availability of shared cars (used selectively when required) reduces incentives to purchase private cars which– once bought– are driven more given their lower marginal usage-costs after the initial fixed-cost investment (Le Vine et al., 2014; Millard-Ball et al., 2005). A recent review in this journal concluded that “[g]reening passenger transport requires a re-think of present vehicle-centered approaches, and a focus on accessibility” (Moriarty and Honnery, 2013, p. 21)– a *focus on accessibility* is the central characteristic of the PSS carsharing.

Automakers increasingly offer carsharing-systems directly to end-customers – a disruptive innovation in one of the largest industries. Carsharing-systems have been tested by automakers in the past, for example by Honda operating Honda DIRACC in Singapore (Byers et al., 2015). However, the year 2009 marked the beginning of a large-scale shift in the automotive industry: Of carsharing-systems in operation, *Daimler* launched the first in 2009 (www.car2go.com), followed in 2010 by *Peugeot* (www.mu.peugeot.co.uk), and in 2011 by *BMW* and *Volkswagen* (https://de.drive-now.com/en/;https://web.quicar.de). In 2012-2013, *Citroën* (www.multicity-carsharing.de/en), *Ford* (www.ford-carsharing.de), *General Motors* (www.onstar.com/web/portal/relayrides-test?g=1), Opel (http://blog.tamyca.de/post/62323417343/tamyca-opelcarsharing), and *Kia* (www.kia.ca/student-car-share-program) launched carsharing-schemes, and in 2014, *Fiat* and *Toyota* (https://enjoy.eni.com/en/milano; http://newsroom.toyota.co.jp/en/detail/mail/3962091). This revolution in the automobile industry was summarized in 2013 by a *BMW*-manager: "You're witnessing a tipping point in the car-sharing market. It's becoming mainstream" (Gibbs, 2013).

But how will "becoming mainstream" affect the sustainability of carsharing-systems? As of December 2014, there are as yet no long-term measurements of the effects of automakers selling mobility instead of cars. Currently, empirical carsharing-evaluations face two central methodological challenges: First, it takes years after a carsharing-system's launch until the impacts stabilize – early impact-studies are therefore no indicator for long-term impacts. For example, a longitudinal study on the carsharing-provider *City CarShare* (San Francisco, USA) found diametrically opposed impacts measured 2 years vs. 1 year after the launch. Two years after *City CarShare's* launch, the study concluded that "[e]vidence of travel suppression stands in stark contrast to first-year impacts wherein members' average VMT [vehicle miles traveled] had increased. Early adopters – many drawn from the ranks of environmentalists and avid cyclists who owned no car – began logging vehicle miles on the streets of San Francisco; over time (…) induced travel appears to have been replaced by reduced travel" (Cervero and Tsai, 2004, pp. 125e126). Similar findings have been reported since the beginning of carsharing-research (e.g. Katzev et al., 2001; Walb and Loudon, 1986). However, increased car usage after the launch of carsharing-systems is assumed to be outweighed by *reduced* private car ownership in the long-term (e.g. Martin and Shaheen, 2010; Meijkamp, 1998). Therefore, following a carsharing-system's launch, the combination of fast adaptation-processes (e.g. zero-car households starting to drive carsharing-cars) and slow adaptation-processes (e.g. households abolishing private cars) shapes the overall carsharing-impact unfolding over time – an unsolved measurement challenge. A second methodological challenge for evaluations of carsharing-systems is the lack of standards: As of December 2014, not a single study-design in the field of empirical carsharing-research has ever been replicated, even so all measured carsharing-impacts strongly depend on the applied measurement-method (Firnkorn, 2012). In addition, empirical carsharing research has so far been dominated by static research designs evaluating carsharing-impacts at a single point in time.

This article proposes a paradigm shift from a *static* to a *dynamic* view on impacts of the PSS carsharing based on a framework structuring static carsharing-evaluations and a generic model of dynamic adaptation-processes of the mobility-behavior of carsharing-users over time. In this article, "framework" refers to a logical structure describing the relationship between research designs, target-parameters, and carsharing-studies, whereas "model" refers to a representation of a real-world phenomenon (Frigg and Hartmann, 2012): Carsharing-induced adaptation-processes of the mobility-behavior of new carsharing-users. The term "generic" is used to indicate an applicability across carsharing system-variants (e.g. with/without fixed vehicle-stations) and across target-parameters (e.g. carsharing-impacts on emissions, modal splits, or private-vehicle holding).

The objective of this article is to advance empirical sustainability-evaluations of carsharing-systems, given that PSS-scholars have repeatedly called for more empirical PSS-research. For example, Boehm and Thomas reported "a lack of quantitative empirical research designs" (Boehm and Thomas, 2013, p. 256), Mont and Tukker indicated that "[t]he challenge in the coming years is to make the research in the PSS field more rigorous and truly systemic in nature" (Mont and Tukker, 2006, p. 1454), Lindahl et al. pointed out a "clear need for publishing more research quantifying the environmental as well as economic benefits" (Lindahl et al., 2014, p. 289), and also Tukker concluded that "[i]t is striking, however, that quantitative research methods (…) are still rarely applied" (Tukker, 2015, p. 88). Given the rare application of quantitative methods, very few analyses of quantitative-empirical research methodology exist in the field. The present article contributes to closing this gap by focusing on the methodological research question: Which generic time- and method-interdependencies exist when shared-mobility impacts are empirically evaluated over time?

The authors of the present article hope that the proposed paradigm shift from a static to a dynamic view on carsharing-impacts does not only remain a theoretical contribution, but rather that this perspective is adopted by policymakers enacting carsharing-regulations in cities. To the knowledge of the authors, *dynamic* adaptation-processes of the mobility-behavior of carsharing-users have so far conceptually and empirically received limited consideration in carsharing-studies, and accordingly, many policymakers currently judge carsharing-schemes with a static view. To maximize the long-term sustainability-gains through carsharing (e.g. private-car reduction), cities may, however, have more success when considering the dynamic and asymmetric unfolding of carsharing-impacts over time as the base for carsharing-related policy-decisions.

Section 2 explains generic carsharing system-variants operating today, gives an up-to-date overview of the growing carsharing-industry, and contrasts the state of theoretical vs. empirical shared-mobility research. Section 3 proposes a framework structuring static carsharing-studies and a generic model of dynamic adaptation processes over time. Section 4 expands the analysis by the consideration of environment-stability. Section 5 summarizes the methodological contributions, and Section 6 reflects on future research.

2. Overview of an expanding mobility-disruption

2.1. Carsharing system-variants

Carsharing-systems exist in three generic system-variants. Sorted by increasing user-flexibility, these are (a) “station-based round-trip”-systems requiring users to return cars to the same station (or zone) where a rental began, (b) “station-based one way”-systems allowing users to return cars at a different station (or zone), and (c) “free-floating”-systems allowing users (GPS-based) to start/end car-rentals anywhere within a city without fixed vehicle-stations. Variant (a) is the traditional form of carsharing, whereas variants (b)/(c) emerged recently. Therefore, the PSS-literature does not yet distinguish between different generic carsharing system-variants.

To differentiate generic carsharing system-variants clearly, their full terms are required. For example, variants (a)/(b) are both “station-based” carsharing-systems while variants (b)/(c) both allow “one-way”-trips. This article takes a system-perspective to differentiate generic carsharing system-variants. Additional attributes, including profit-orientation, ownership, and legal form of carsharing-systems, can be used to classify finer sub-variants (e.g. “peer-to-peer”-carsharing is a variant in which private persons offer their cars to other private persons through a “station-based round-trip”-system). The generic model of dynamic adaptation-processes proposed in this article is applicable to all generic system-variants of carsharing-systems.

2.2. Carsharing-growth and shared-mobility research

2.2.1. The emergence of a shared-mobility industry

Carsharing is skyrocketing internationally. In addition to automakers (Section 1), new players in the carsharing-industry include rental car companies (e.g. *Avis*, *Europcar*, *Hertz*, *Sixt*) and a railway-corporation (*Deutsche Bahn* –

offering carsharing-vehicles in 140 German cities). Traditional carsharing-companies also expand and diversify (Shaheen and Cohen, 2013), and consequently industry-definitions in the mobility-sector are becoming blurred. The big picture is: The PSS carsharing is currently morphing from a niche into a mainstream mode of transportation, as reflected in Fig. 1.

Fig. 1 compares Germany and North America because for Europe no aggregated growth data exists. Fig. 1 shows that the number of carsharing-users more than tripled from 2010 to 2014 in both regions. However, the carsharing-growth reflected in Fig. 1 constitutes just a part of the expanding shared-mobility industry, which also comprises non-carsharing PSS, including *scooter*-sharing (e.g. www.scootnetworks.com; www.motitworld.com/eng) and *bike*-sharing systems (e.g. https://www.citibikenyc.com/; http://en. velib.paris.fr).

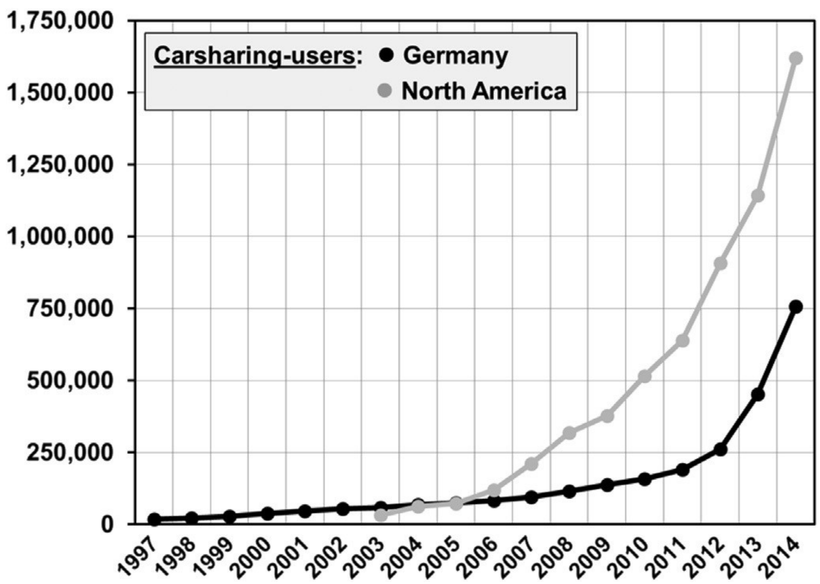

Fig. 1. Growth of carsharing-users in Germany and North America 1997–2014. Sources: bcs, 2014; Shaheen and Cohen, 2014. Reporting-month for Germany: January; North America: July.

The previous shared-mobility examples are from Europe and North America – but “it is in Asia where rapid urban transformation poses the greatest challenge. Between 1990 and 2010, Asia added 754 million urban inhabitants, more than the total population of the United States and Western Europe combined (…) [and in Asia] one billion more people will become urban residents in the next 25 years” (Puppim de Oliveira et al., 2013, p. 1). Currently, few shared-mobility systems operate in Asia relative to Europe and North America (an exception is Japan), but this could change soon on an unprecedented scale. For example, the city of Hanghzhou, China launched a bikesharing-system with more than 60,000 bicycles in 2008 (Shaheen et al., 2011; Streetfilms, 2011), and in 2013 a carsharing-system which will offer up to 100,000 electric cars (Kandi Technologies, 2013; Rogowsky, 2013). In India, where by 2030 there will be more inhabitants than in China (United Nations, 2012), the country's first carsharing-system started in Bangalore in 2013 (www.zoomcar.in). However, despite the international expansion of the shared-mobility industry, no model to evaluate the sustainability of carsharing-systems over time has yet been proposed.

2.2.2. The trailing emergence of empirical shared-mobility research

Among the early scholars thinking about carsharing-impacts were PSS-researchers. For example, the first article in the Journal of Cleaner Production mentioning “carsharing” (or car sharing/carsharing) was published by Oksana Mont in 2002 under the title *Clarifying the concept of product–service system* (Mont, 2002). In 2002, carsharing was a marginal phenomenon (Fig. 1), and accordingly Mont argued: “Consumers might not be very enthusiastic about ownerless consumption (…). The successful models such as car sharing are still limited to small market niches” (Mont, 2002, p. 244). During the past decade, carsharing-research has grown in parallel with the industry's expansion – as of December 2014 there were 61 articles in this journal mentioning “carsharing” (or car sharing/car-sharing), of which more than half have been published since 2012. But what do we know empirically about carsharing-impacts?

Quantifying carsharing-impacts is complex. The *empirical* shared-mobility literature shows that “[n]umerous social and environmental benefits are commonly associated with carsharing, supported by an increasing body of empirical evidence. However, differences in data collection and study methods frequently produce inconsistent results, often with limited samples” (Shaheen and Cohen, 2007, p. 82). In contrast, the *theoretical* PSS-literature tends to give carsharing a universal leap of faith regarding sustainability-benefits. For example, Chou et al. argued that “[t]he most common examples in PSS are sharing, renting, and leasing (…). The carsharing scheme is a representative model that changes consumers' behavior of the private ownership, reducing the number of cars and the production waste” (Chou et al., 2012, p. 174). Indeed, most publications indicating carsharing as a PSS-example assume sustainability-gains (e.g. Beuren et al., 2013; Gaiardelli et al., 2014; Geum and Park, 2011; Lim et al., 2012; Liu et al., 2007; Manzini and Vezzoli, 2003; Walz, 2011), and many positive impact-assumptions regarding carsharing are likely to be correct.

However, the growth of the shared-mobility industry raises new questions regarding carsharing-impacts. Will the industry's current growth trajectory (Fig. 1) scale up carsharing-impacts proportionally or change them? What will be the effects of multinational corporations (Section 1) entering the carsharing-sector? And will different carsharing system-variants (Section 2.1) have different impacts over time? Years of empirical research and new measurement-methods are required to answer such questions. While much work is needed to advance empirical sustainability-evaluations of carsharing-systems regarding various methodological aspects (Firnkorn, 2012), this article focuses on the measurement-challenge to evaluate carsharing-systems *over time*. First, because the measurement point-in-time is one of the strongest parameters influencing the results of any carsharing impact-study. Second, because no model has previously been proposed to do this.

Linking *static* impact-measurements to *dynamic* adaptation-processes is a prerequisite for a holistic understanding of the impacts of carsharing-systems. No matter whether, for example, carsharing-studies forecast emission-impacts (Firnkorn and Müller, 2011) or retrospectively report on private vehicle reduction (Firnkorn and Müller, 2012) e such singular snapshots of multi-year, complex, and ongoing adaptation-processes have a limited value without the context of a general theory of dynamic adaptation-processes *over time*. Given that this article is a first attempt to explain carsharing-impacts dynamically through the behavioral change of carsharing-users over time e the proposed adaptation-model will leave room for debate. However, if future papers discuss this article's shortcomings and develop refined adaptation-models, the proposed paradigm shift from a static to a dynamic view on carsharing-impacts would have succeeded, which the authors believe would benefit all cities enacting regulations based on measured or assumed impacts of the PSS carsharing.

3. Adaptation-processes over time define the applicability of generic research designs

3.1. A framework structuring static carsharing-studies

A framework structuring empirical carsharing-studies on a high level of abstraction, before measurement-details are discussed, is helpful to distinguish generic methodological decisions from measurement-technicalities. For example, some authors have argued that carsharing-impacts must always be measured as *hypothetical impacts* (e.g. Haefeli et al., 2006) by asking carsharing-users how they would hypothetically cover their mobility-needs today, if their currently used carsharing-system was not offered. In contrast, other authors have advocated measuring *retrospective impacts* (e.g. Cervero et al., 2007) by comparing the mobility-behavior before and after people join carsharing-schemes. Further generic measurement-approaches exist (Firnkorn, 2012), and combinations can also be applied (e.g. Martin and Shaheen, 2010) – as long as the research community does not agree on such general methodological conventions, standardized (and thereby comparable and generalizable) impact-measurements will not be achieved for any carsharing system-variant (Section 2.1), independent of the considered target parameter (e.g. carsharing-impacts on emissions, modal splits, or private-vehicle holding) and measurement-technicalities (e.g. weighting monthly measurement-points based on annual mobility-cycles; correcting non-response biases).

The research community currently disagreeing about general methodological conventions could benefit in three ways from a framework structuring carsharing-studies. First, a framework enables a structured analysis of previous carsharing-studies. Second, generic advantages and disadvantages of possible future research designs can be explained more clearly (i.e. separate from technicalities) within the structure of a framework. Clear explanations of proposed standardized impact-measurements will in turn increase the probability of their replication, because standardized methods are not established by anyone naming them “standardized” but rather through their acceptance and continuous replication in the field. Third, a framework establishes a consistent methodological vocabulary. For example, the term “before-and-after study” has been used in different carsharing-studies to denote longitudinal or cross-sectional research designs (e.g. Cervero et al., 2007; Martin and Shaheen, 2010). While the different applied methods become clear when reading the full studies, a consistent vocabulary based on precise research-design definitions could facilitate the methodological discussions within the research community as well as conversations with external cooperation partners (e.g. national legislators and city councils making policy-decisions based on reported carsharing-impacts).

A framework with the dimensions “(1) Generic research design” and “(2) Target parameter” can structure all *static* carsharing impact-measurements on a high level of abstraction, as displayed in Fig. 2.

The left side of Fig. 2 displays *generic research designs* to evaluate carsharing-impacts through cross-sectional or longitudinal measurement-approaches. This categorization is applicable for every target parameter and carsharing system-variant (Section 2.1). The right side of Fig. 2 displays three common *target parameters* together with exemplary empirical carsharing-studies, cross-tabulated with the research designs on the left.

Fig. 2 shows that cross-sectional research designs based on a single point of data collection (DC) in time (t) allow impact-calculations by comparing a status of today with the past, a hypothetical situation today, or the future. In contrast, longitudinal research designs based on two (or more) points of data collection in time allow impact-calculations by comparing a status of today with a *measured* status in the past without carsharing-users having to *remember* their past mobility-behavior as in cross-sectional research designs. As a simplification, this article uses “2 DC” to indicate the methodological principle of all longitudinal research designs, which may have a greater number of data collection points over time.

The exemplary study (Fig. 2) by Firnkorn and Müller (2012) used a single survey asking carsharing-users for their private vehicle holding today and in the past – a generic research design of the type *retrospective impact* (1× DC). In contrast, the study by Haefeli et al. (2006) asked carsharing-users how they would hypothetically behave today, if their currently used carsharing-system was not offered (e.g. Would they hypothetically buy a car today without carsharing?) – a generic research design of the type *hypothetical impact* (1× DC). Although the former two cross-sectional approaches (measuring retrospective impacts vs. hypothetical impacts today) dominate carsharing-research (e.g. Martin and Shaheen, 2010), their interplay remains conceptually and empirically largely unexplored (Firnkorn, 2012). A third generic cross-sectional research design is exemplified by the study of Firnkorn and Müller (2011), which asked new carsharing-users for their planned future mobility-changes due to carsharing – a research design of the type *future impact* (1× DC). The exemplary study by Cervero et al. (2007) collected data through five surveys answered over several years by users of the same carsharing-provider – a generic research design of the type *retrospective impact* (2× DC).

The framework in Fig. 2 extends a classification proposed previously in the literature (Firnkorn and Müller, 2011), but it remains incomplete. While the generic research designs on the left side of Fig. 2 are mutually exclusive and collectively exhaustive, the exemplary target parameters on the right side share neither characteristic. Other target parameters can be considered, and target parameters can also be interdependent, depending on their exact definition (e.g. private-vehicle reduction influences CO2- impact-evaluations if avoided vehicles are considered in emission-analyses). Furthermore, some target parameters are only indirectly affected by carsharing-schemes. For example, decreasing car ownership through carsharing-systems can reduce required parking areas in cities, which may lead to less storm-water runoff (Millard-Ball et al., 2005). However, the purpose of Fig. 2 is not completeness, but rather to contribute a structured thought pattern and consistent methodological vocabulary to the current discussion about approaches to measure impacts of the PSS carsharing.

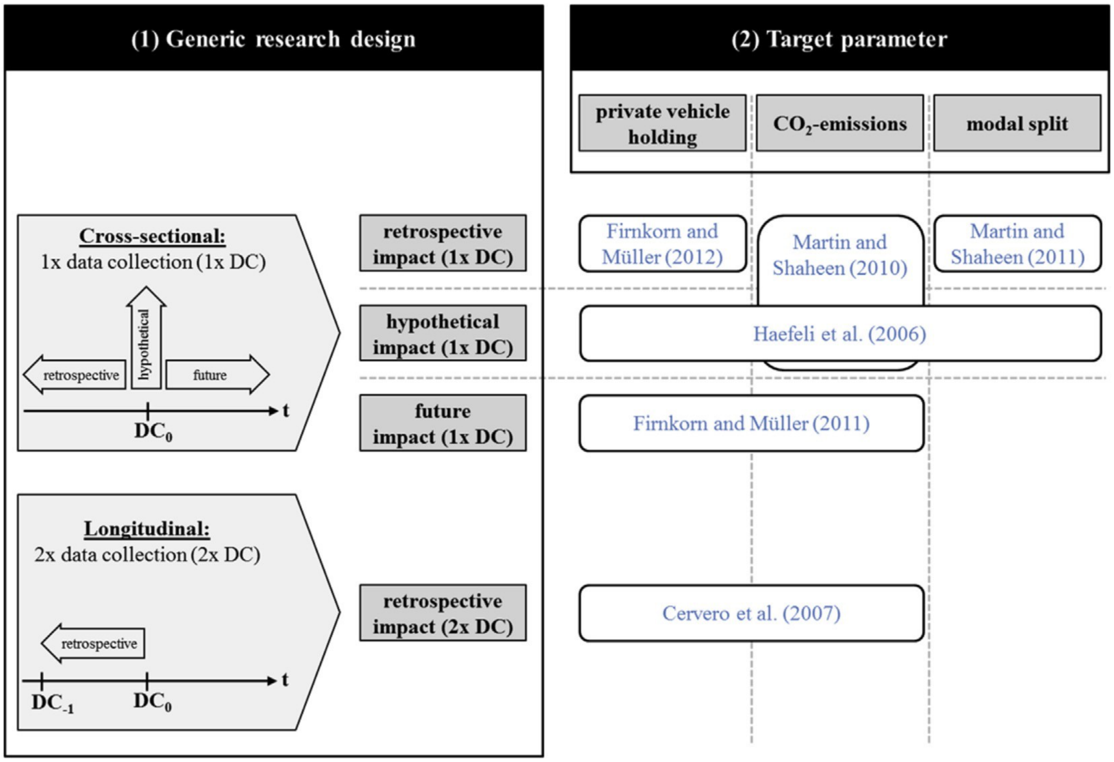

Fig. 2. Framework structuring static carsharing-studies.

3.2. A generic three-phase model of dynamic adaptation-processes over time

Adaptation-processes over time define the applicability of generic research designs (Fig. 2) dependent on the phase after a carsharing-system's launch. In this article, "applicability" of generic research designs (in different phases) is defined as "measuring an impact unequal to zero". For example, measuring a retrospective impact directly after the launch of a carsharing-system (when users have not yet adapted their mobility-behavior) would capture zero impact, as would asking for future impacts after carsharing-users have completely adapted their mobility-behavior (when no more changes will occur). Given that all carsharing-evaluations are similarly time-dependent, the attribute *time-dependency* can be used to structure generic research designs (Fig. 2) based on their applicability-over-time along the dimension "(3) Phase after launch", as displayed in Fig. 3.

Fig. 3 shows three generic phases after the launch of a carsharing-system together with applicable research designs for each phase.

Phase A is the initial phase in which *User-generation 1* adapts its mobility-behavior. This includes fast adaptation-processes occurring over months (e.g. zero-car households starting to drive carsharing-cars), and slow adaptation-processes occurring over years (e.g. households abolishing private cars). *User-generation 1* comprises all users having joined the launched carsharing-system until its impacts stabilize – the point when repeated static impact-snapshots over time converge towards the same result. During *Phase A*, all generic research designs (Fig. 2) can be applied to measure carsharing-impacts, but only at specific points within *Phase A* – please see the "applicability"-definition at the beginning of this section.

Phase B is reached when *User-generation 1* has completed the carsharing-induced adaptation of its mobility-behavior. This means that all fast and slow adaptation-processes have ended, having transformed the mobility-behavior of *User-generation 1* from an old to a new equilibrium. This is a model-simplification, because adaptation-processes never "end" (they may even be considered infinite). However, the sufficient adaptation of most carsharingusers' mobility-behavior allows a conceptual demarcation between the first two model-phases: Before (*Phase A*) vs. after (*Phase B*) carsharing-impacts have stabilized as the result of sufficiently completed adaptation-processes. The transition point from *Phase A* to *Phase B* is therefore defined by a change in the applicable research designs. While during *Phase A* users can be asked for their planned future mobility-changes due to carsharing, *Phase B* is (by definition) a phase in which the initial adaptation-processes have been completed, thus future-oriented impact-measurements (i.e. the research design *future impact* (1× DC)) are no longer applicable. In contrast, retrospective-oriented impact-measurements (i.e. the research designs *retrospective impact* (1× DC; 2× DC)) remain applicable in *Phase B*, provided studies in *Phase B* compare a status in *Phase B* with a status in *Phase A* – whereby the status in *Phase A* can be *remembered* (cross-sectional designs) or *measured* (longitudinal designs) (Section 3.1).

Phase C is reached through the long-term generational change in the user-base. *User-generation 1* consists of people having changed their mobility-behavior because of carsharing – but in the distant future there will be a *User-generation Z* growing up with carsharing, and these users will lack a "before-carsharing"-state. This effect should be anticipated by the research community because in *Phase C* all research designs using retrospective impact-measurements will become inapplicable – which may limit the future applicability of evaluation-methods developed today, depending on their generic research design (Fig. 2). As a modelsimplification, *User-generation Z* is defined as a homogenous group becoming carsharing-users (instead of private-vehicle holders) after obtaining their driving license. The transition from *Phase B* to *Phase C* is therefore defined by another change in the applicable generic research designs. While during *Phase B* users can be asked for their pre-carsharing mobility-behavior, *Phase C* is (by definition) a phase in which retrospective-oriented impact-measurements (i.e. the research designs *retrospective impact* (1× DC; 2× DC)) are no longer applicable. In contrast, the generic research design *hypothetical* *impact* (1× DC) remains applicable in *Phase C*, because carsharing-users of *User-generation Z* (lacking a “beforecarsharing”-state) can be asked how they would hypothetically cover their mobility-needs without their used carsharing-system (e.g. Would they hypothetically buy a car without carsharing?).

The purpose of the generic three-phase model (Fig. 3) is to illustrate that adaptation-processes define the applicability of generic research designs (Fig. 2) over time. This time-dependency applies to impact-evaluations across carsharing system-variants (e.g. systems with or without fixed vehicle-stations) and across target-parameters (e.g. carsharing-impacts on emissions, modal splits, or private-vehicle holding). The proposed model distinguishes (by definition) three generic adaptation-phases in which different research designs can be applied. Given that the model is generic, it is independent of the complexity of operationalized research designs, and therefore the model can equally be applied for target parameters constructed simply or based on complex operationalizations, for example considering rebound effects (Figge et al., 2014; Spielmann et al., 2008).

Fig. 2 and Fig. 3 jointly introduced three dimensions holistically defining the three-dimensional possibility space of empirical carsharing-evaluations: (1) Generic research design, (2) Target parameter, and (3) Phase after launch – a “How/What/When”- tuple sufficiently describing every empirical sustainabilityevaluation of carsharing-systems on an abstract level.

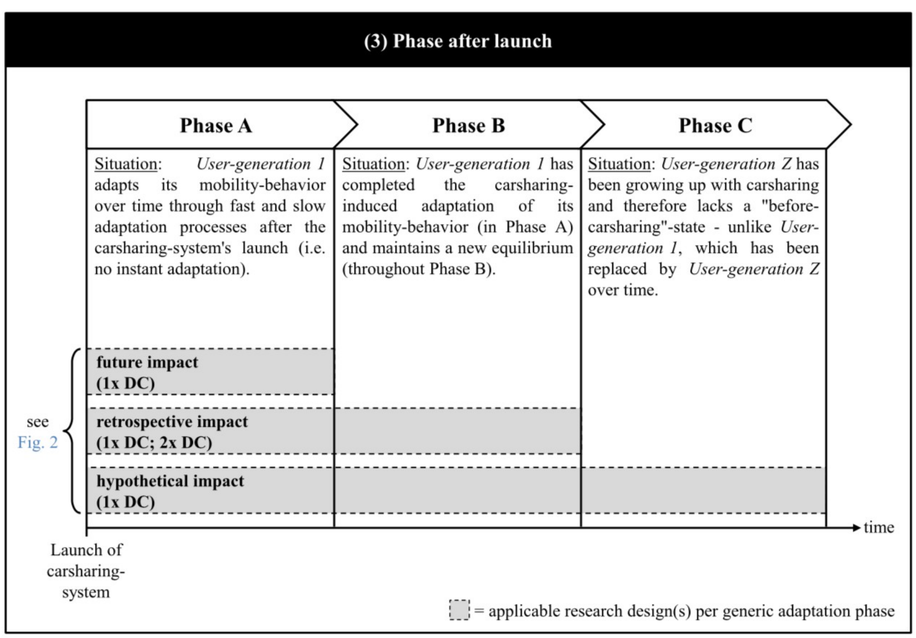

Fig. 3. Generic three-phase model of dynamic adaptation-processes and applicable research designs over time.

3.3. An exemplary application of the generic three-phase model

To illustrate how the proposed three-phase model (Section 3.2) may support policymakers through increased clarity regarding the time-dependency of carsharing-impacts, this section discusses an exemplary application of the model to the target parameter *vehicle kilometers traveled* (VKT), illustrated in Fig. 4.

Fig. 4 displays a theoretical adaptation-process triggered by the launch of a carsharing-system. This is an illustration of an exemplary development of the target parameter VKT over time – it is not a generalizable adaptation-curve. Given that this article is a first attempt to explain carsharing-impacts dynamically, no dataset exists to which an exemplary adaptation-curve could be fitted. However, the authors hope that the proposed paradigm shift from a static to a dynamic view on carsharing-impacts will lead to empirical work allowing the quantitative analysis of adaptation-processes over time in future research.

The purpose of Fig. 4 is to illustrate the idea to view carsharing-impacts *dynamically* over the generic adaptation-phases defined in Fig. 3. The horizontal axis shows the time after a carsharing-system's launch (non-linear scale), while the vertical axis indicates the target parameter VKT – the exact vertical positions of *Points (2)*, *(4)*/ *(5)*, and *(6)* do not matter. Despite the similarity of the terms “adaptation” and “adoption”, models of innovation-diffusion, including “innovator/early adopter/majority”-models by Everett Rogers (2003), are unrelated to Fig. 4.

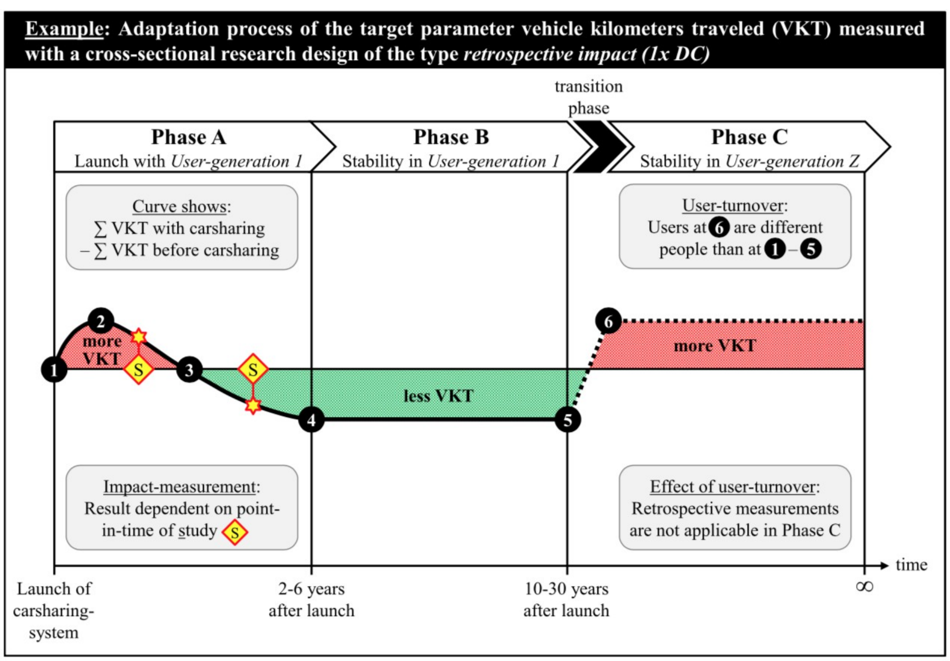

Fig. 4. Exemplary application of the three-phase model of dynamic adaptation-processes.

The considered target parameter VKT is assumed to be measured using a cross-sectional research design of the type *retrospective impact* (1× DC) (Fig. 2). First, because this is a comparatively non-complex research design easy to discuss. Second, because it is the most common research design in empirical carsharing-studies. The research design *retrospective impact* (1× DC) asks carsharing-users two central questions to determine the VKT-impact: “How many kilometers do you travel in cars today?” and “How many kilometers did you travel in cars *before* becoming a carsharing-user?”. Studies differ in their system-boundaries, for example, kilometers traveled in taxis, rental cars, and cars borrowed from friends/family have been considered differently in empirical carsharing-studies, whereas kilometers traveled in carsharing-vehicles and own private cars (registered to the name of the respondent) are always included. In short: Retrospective research designs calculate the VKT-impact of a carsharing-system based on the principle “ΣVKT with carsharing today SVKT before carsharing” (Σ denoting the sum over all carsharing-users in a sample).

Phase A is the initial phase in which *User-generation 1* adapts its mobility-behavior. Point (1) marks the launch of the carsharing-system, and Points (2)–(4) illustrate the case of an initial increase and subsequent decrease of the SVKT. This effect was detected empirically in a longitudinal study on the carsharing-provider *City CarShare* in San Francisco (Cervero, 2003; Cervero and Tsai, 2004; Cervero et al., 2007), described in Section 1. The exemplary border between *Phase A* and *Phase B* at “2e6 years after launch” reflects Cervero and Tsai's finding that carsharing-impacts had not stabilized “2” years after *City CarShare's* launch (Cervero's last survey 4 years after *City CarShare's* launch showed different impacts; whether impact-stability had been reached after 4 years is unknown). The upper border-value “6” years is an exemplary estimate by the authors of the present article (given the lack of empirical studies). The phase-borders in Fig. 4 are only examples to illustrate the demarcation-logic when conceptualizing carsharing-impacts as adaptation-processes over time – the exact border-values therefore do not matter and will differ for each individual local carsharing-system.

Phase B is reached when *User-generation 1* has completed the carsharing-induced adaptation of its mobility-behavior. This means that at Point (4) all fast and slow adaptation-processes (Section 3.2) have ended, having transformed the mobility-behavior of *User-generation 1* from an old to a new equilibrium. The border between *Phases B* and the transition phase to *Phase C* at “10–30 years after launch” is an exemplary estimate by the authors of the present article (no carsharing-system worldwide operates in Phase C as of 2014).

Phase C is reached through the long-term generational change in the user-base. Such a change will differ for each individual carsharing-system (e.g. affected by the dynamics of people moving into and out of a carsharing-provider's operating area). While *User-generation 1* changes its mobility-behavior due to carsharing, *User-generation Z* grows up with carsharing and lacks a comparable "before-carsharing"-state (see the definition of *User-generation Z* in Section 3.2) – retrospective research designs are therefore no longer applicable in *Phase C*. Point (5) marks the beginning and Point (6) the completion of the generational change in the user-base with the curve's gradual increase in the transition phase reflecting the natural user-turnover over time. Comparing the mobility-behavior "before-and-after" (Section 3.1) people become carsharing-users could only find a VKT-increase in *Phase C*, a situation discussed by Martin and Shaheen: "If carsharing was entirely populated by people who were not driving prior to joining, then the observed impact could only be positive [here: positive ¼ more emissions], as carsharing would provide additional automotive access to people who were not driving before" (Martin and Shaheen, 2010, pp. 47e48).

Is carsharing sustainable? In the example in Fig. 4, an empirically determined answer would be time-dependent because a static impact-study conducted between *Points (2)* and *(3)* would find a VKT-increase, whereas the same study conducted between *Points (3)* and *(4)* would find a VKT-decrease (see yellow S-symbols in Fig. 4). The possibility of such asymmetric impacts unfolding over time is the reason the present article proposes a paradigm shift from a static to a dynamic view on impacts of the PSS carsharing.

Fig. 4 illustrates a single example not representing the plurality of carsharing-impacts. The run of the exemplary curve in *Phase A* is based on the longitudinal study on *City CarShare* (Cervero, 2003; Cervero and Tsai, 2004; Cervero et al., 2007), whereas in *Phase B* and *Phase C* it is based on model-assumptions (new equilibrium and user-turnover; see Section 3.2). However, the study on City *CarShare* in San Francisco is unreplicated as of December 2014, and it is therefore unknown how carsharing-impacts may unfold in cities with other characteristics (e.g. demographics, mobility-culture, public transportation network). Also, other model-assumptions can be made.

Furthermore, different target parameters will have different adaptation-processes over time. For example, the VKT-curve in Fig. 4 could look similar to a curve of the target parameter *emission-impact* for the same carsharing-provider (as VKT and emissions are likely to be correlated), but simultaneously the VKT-curve could look different from a curve of the target parameter *private vehicle holding* (because of fast and slow adaptation-processes influencing different target parameters differently over time; see Section 3.2).

In addition, adaptation-curves over time fundamentally depend on the generic research design. This applies even when all other factors are constant, in particular the considered target parameter and the individual carsharing-provider being evaluated. For example, Fig. 4 illustrates a VKT-curve assumed to be measured using the research design *retrospective impact* (1× DC). However, this curve would look different if it was based on the research design *hypothetical impact* (1× DC), which asks carsharing-users two central questions to determine the VKT-impact: "How many kilometers do you travel in cars *today*?" and "How many kilometers would you travel in cars *today* without carsharing?". In short: Research designs contrasting the status today with the alternative status today if carsharing was not offered calculate the VKT-impact of a carsharing-system based on the principle "ΣVKT with carsharing *today* ΣVKT without carsharing *today*". Given that some carsharing-users would buy private cars and thereby drive more in cars in total if carsharing was not offered, the research design *hypothetical impact* (1× DC) could, for example, show a VKT-reduction in *Phase C* – the opposite of the curve in Fig. 4 (all factors except the generic research design being equal).

3.4. The quest for a generalizable methodological principle

Policymakers viewing carsharing-impacts as time- and method-dependent can improve policy-decisions. For example, a German city council issued only temporary parking licenses required for the local operation of new free-floating (Section 2.1) carsharing-systems. The city council argued that because the impacts of free-floating carsharing-systems are unknown, an impact-evaluation in the third year after the local launch would be used to decide on the carsharing-systems' continuation in the city. But is a new equilibrium reached by the third year? Will the third-year impact-evaluation represent the carsharing-systems' long-term impacts in the city? As of December 2014, no dataset exists to provide an empirical answer (Fig. 4 cannot be generalized). Independent of the case of this German city council: What if a carsharing-system is terminated because of an early static impact-snapshot not reflecting the long-term sustainability-gains that a city would achieve by keeping the carsharing-system?

Policymakers should also view carsharing-impacts as method-dependent. For example, most carsharing-evaluations conducted in the Western world (e.g. Germany, USA) have used methodological variants comparing the mobility-behavior before and after people become carsharing-users. If this "before-and-after" methodological approach was applied in China, where a growing number of middle class households will either purchase a first private car or alternatively stay private-car-free and selectively use carsharing (where offered), the Western "before-and-after" evaluation-tradition could only find a VKT-increase through carsharing-systems – analogous to *Phase C* in Fig. 4. In contrast, the generic research design *hypothetical impact* (1× DC) would find the opposite result, given that Chinese citizens foregoing a private car purchase because of carsharing would alternatively buy private cars and thereby drive more in cars in total if carsharing was not offered. Would it be a wise policy-decision if Chinese city councils prevented the widespread implementation of carsharing-systems when local "before-and-after"-studies concluded that Chinese citizens drive more in cars after joining carsharing-schemes, compared to the situation before – when most of them never drove cars at all?

The results of any carsharing-evaluation fundamentally depend on the generic research design. Which research design should cities then consider when developing impact-based policies aimed to maximize sustainability-gains through carsharing? Is it possible to articulate a generalizable methodological principle as the base for all evaluations of the PSS carsharing?

4. The influence of environment-stability on research-design usability

4.1. Relative sustainability: What if a carsharing-system was not offered?

This article views sustainability as a relative concept. Absolute sustainability would demand that carsharing-systems strive for zero environmental impacts. This purist view, however, limits impact-discussions to efficiency-considerations, offers no guidance for long-term development strategies, and "may lead to a rather unconstructive sense of cultural pessimism, since all human activities are perceived as being inherently harmful to the environment" (Bjørn and Hauschild, 2012, p. 325). In contrast, relative sustainability asks for the alternative if a carsharing-system was not offered. For example, would there be more or less emissions without carsharing? Would traffic congestion increase or decrease? Would more or fewer citizens use public transport? This relative perspective allows the articulation of a generalizable methodological principle to guide research design developments: *Compare today's carsharing-situation to today's situation if carsharing was not offered.*

Today's situation if carsharing was not offered is unobservable. However, it would not necessarily be the unchanged past situation before a considered carsharing-system was launched, as an unstable local environment can change over time independent of the local introduction of a carsharing-system, as illustrated in Fig. 5.

Fig. 5 illustrates three generic carsharing-environments with varying degrees of stability. This article defines "environment" as all physical and non-physical stimuli influencing the mobility-behavior of carsharing-users over time (e.g. transportation infrastructure; smartphones apps; societal value system; mobility-culture). The term "stability" expresses the environment's change independent of carsharing. In Fig. 5, each row shows the same environment (=rectangle) before (left) and after (right) a carsharing-system is launched. The carsharing-users' mobility-behavior (=black circle) is an element enclosed by the environment – metaphorically a billiard-table with a billiard-ball at the positions (T0) and (T1). The speed of environment change and the speed of carsharing-induced change are represented in the metaphor by the billiard-ball's velocity (=change/time), whereas in applied research designs the analogy depends on the considered target parameter of empirical carsharing-studies. For example, the target parameter "private vehicle holding" (Fig. 2) can change over time for various reasons unrelated to carsharing, including rising gasoline-prices, new parking-regulations, the economic development of a region, and changing population demographics. Measuring empirical shared-mobility impacts beyond singular snapshots of ongoing adaptation-processes requires studies to evaluate impacts over a sufficiently long period following the local launch of a carsharing-system (Fig. 3; Fig. 4) – but longer assessment-periods simultaneously increase the probability of factors unrelated to carsharing having influenced the evaluated target parameter over time, which introduces a bias to all retrospective impact measurements ("before-and-after").

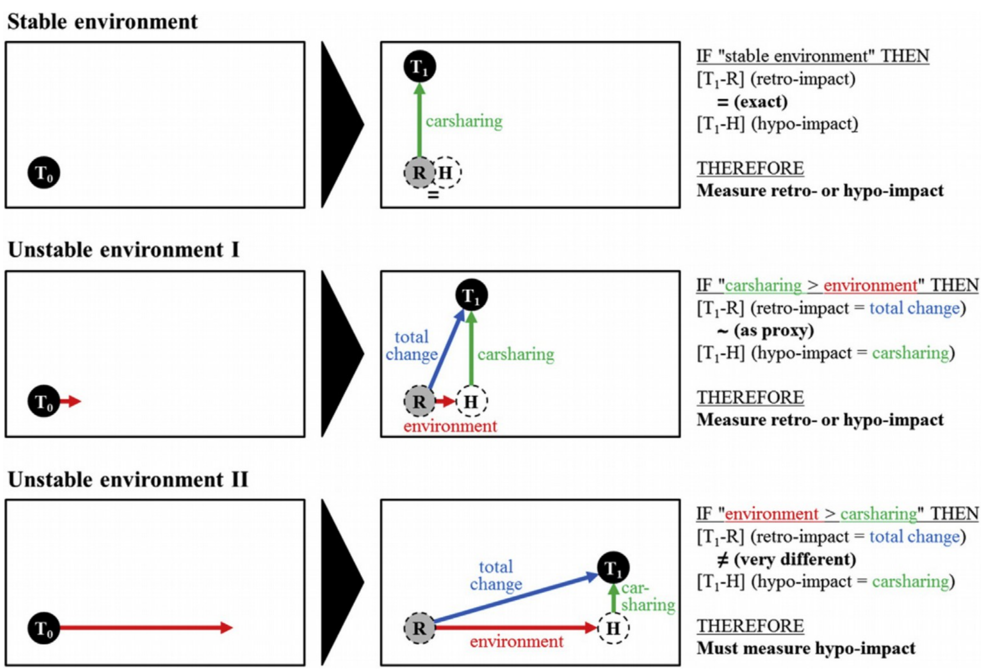

Fig. 5. Environment-stability influences the usability of generic research designs.

The top row of Fig. 5 shows a *Stable environment*. In the left rectangle, the pre-carsharing mobility-behavior (T_0) of the prospective carsharing-users is assumed to be stable without the launch of a carsharing-system.

The stable environment means that the billiard-ball (=mobility-behavior) on the left (T_0) lies motionless on the billiard-table (=environment). In the right rectangle, the billiard-ball has moved to the position (T_1) due to carsharing. The billiard-metaphor's two-dimensional simplification does not affect the argument that environment-stability influences research design usability (an *n*-dimensional vector could express the *n*-dimensional reality).

What is the carsharing-system's impact in the top row of Fig. 5? One perspective would be to compare the new status (T_1) with the old status (T_0) before the carsharing-system was launched – the former status (T_0) is indicated by the billiard-ball's retrospective position (R) in the right rectangle. Another perspective would be to compare the new status (T_1) with the hypothetical status (H) today, if the carsharing-system had not been launched. In a Stable environment, (R) is by definition identical to (H), and thus the two impact-measurements "retro-impact" [T_1-R] and "hypo-impact" [T_1-H] generate the exact identical result. The term "retro-impact" is used to abbreviate the generic research designs *retrospective impact* (1× DC; 2× DC), while "hypo-impact" represents the generic research design *hypothetical-impact* (1× DC) (Fig. 2). Therefore, researchers evaluating a PSS carsharing in a stable environment can interchangeably measure the retro- or hypo-impact.

The middle row of Fig. 5 shows an *Unstable environment I*. This case assumes a minor carsharing-independent environment-change, and a larger carsharing-induced change (the arrows' length in Fig. 5 represents the magnitude of change). In the right rectangle, the billiard-ball's retrospective position (R) is relatively close to its hypothetical position without carsharing (H), and thus the total change (blue arrow) approximates the carsharing-induced change (green arrow). Therefore, researchers evaluating a PSS carsharing in an unstable environment with an environment-change smaller than the carsharing-induced change can measure the hypo-impact, or the retro-impact as a proxy.

The bottom row of Fig. 5 shows an *Unstable environment II*. This case assumes a major carsharing-independent environment-change, and a smaller carsharing-induced change. In the right rectangle, the billiard-ball's retrospective position (R) is relatively distant to its hypothetical position without carsharing (H), and thus the total change (blue arrow) is very different from the carsharing-induced change (green arrow). Therefore, researchers evaluating a PSS carsharing in an unstable environment with an environment-change larger than the carsharing-induced change must measure the hypo-impact. Ongoing change-processes can transform an "Unstable environment I" into an "Unstable environment II", or the reverse, if the carsharing-users' mobility-behavior is considered over more than two periods (T_0) and (T_1).

What is the commonality of the retro- and hypo-impact? It is the methodological principle to construct impacts by *comparing today's carsharing-situation to today's situation if carsharing was not offered*. The only difference is the approach to construct “today's situation if carsharing was not offered”. The retro-impact compares two observable states (T_1) and (T_0) [=(R)], and uses (T_0) as a proxy for (H) – this approach may increase measurement-precision, but it leads to measurement-biases in the case of unstable environments (Fig. 5). In contrast, the hypo-impact compares an observable state (T_1) with an unobservable state (H) – this approach avoids measurement-biases from unstable environments, but it may decrease measurement-precision as the hypo-impact requires researchers to determine the hypothetical mobility-behavior today, if carsharing was not offered (e.g. by asking carsharing-users for their alternative mobility-behavior without carsharing).

A universal recommendation to measure the retro- or hypo-impact cannot be made, given the heterogeneous environment-stability states in which carsharing-systems are launched and the plurality of research questions. However, reflecting on the ratio of environment-change vs. carsharing-induced change over time (Fig. 5) is a constructive starting-point to develop precise research designs for empirical evaluations of carsharing-systems given generic methodological trade-offs regarding complexity and measurement precision. For policymakers, the consideration of “hypothetical impacts” is crucial – avoided private cars in cities due to carsharing-systems are real (or at least a very real impact), even though they cannot be directly observed. On an abstract level, there is no conflict among the research community currently disagreeing about general methodological conventions (Section 3.1): Scholars arguing that carsharing-impacts must always be measured as hypothetical impacts (e.g. Haefeli et al., 2006) and authors advocating the measurement of retrospective impacts (e.g. Cervero et al., 2007) apply the same methodological core principle by constructing today's situation if carsharing was not offered – their methodological disagreement is more rhetoric than fundamental.

4.2. Exemplary application: Countries with saturated vs. non-saturated car markets

Car markets influence the environment-stability of carsharing-systems. For example, the USA have 786 motor-vehicles per 1,000 inhabitants, whereas China has 69 motor-vehicles per 1,000 inhabitants (World Bank, 2014a; reference-year 2011). Vehicle-per-capita ratios are highly definition-dependent (Word Bank, 2014b), are determined primarily by GDP per capita (Dargay et al., 2007; Kahn Ribeiro et al., 2007; Meyer et al., 2012), and may change rapidly in non-saturated car-markets (Rapoza, 2013). The big picture is: The USA have a *saturated* car market with

10 more motor-vehicles per capita compared to China's *non-saturated* car market. What are the implications for evaluations of carsharing-systems in the USA vs. China?

Carsharing-evaluations must consider the local environment-stability. Fig. 5 illustrates that retro-impacts may be used as a proxy for hypo-impacts in slightly unstable environments, whereas highly dynamic environments require the measurement of hypo-impacts. The saturated car market in the USA is a “Stable environment” or “Unstable environment I”, allowing the measurement of hypo-impacts or retro-impacts as a proxy. In contrast, China's non-saturated car market is an “Unstable environment II” in which hypo-impacts must be measured – because retro-impacts would not be a sufficiently precise proxy for carsharing-impacts unfolding in China's rapidly changing mobility-environment. Therefore, the methodological principle “*Compare today's carsharing-situation to today's situation if carsharing was not offered*” (Section 4.1) can be applied in both countries, but policymakers and researchers in the USA and China must use different generic research designs to evaluate the impacts of local carsharing-systems – a difference that must be considered in impact-based carsharing-policies.

The saturation-degree of car markets is just one exemplary factor of environment-stability. For example, rising gasoline-prices and new parking-regulations change citizens' mobility-behavior over time independently of carsharing-systems – environment-stability must be reflected holistically. The proposed paradigm shift from a static to a dynamic view on carsharing-impacts may therefore, in addition to clarifying the time- and method-dependency of carsharing-evaluations (Section 3), help policymakers to better understand the influence of local environment-stability on locally measured carsharing-impacts (Section 4).

5. Contributions

5.1. Contribution to the research field

This article proposed a paradigm shift from a static to a dynamic view on carsharing-impacts. Based on a generic three-phase model of *dynamic* adaptation-processes over time, the *time*- and *method-interdependencies* of empirical carsharing-evaluations were analyzed (Fig. 2; Fig. 3) – a policy-relevant discussion as cities may have to bear short-term negative externalities to gain long-term benefits from carsharing (Fig. 4). In addition, the expanded methodological analysis discussed the influence of generic states of environment-stability on the usability of generic research designs (Fig. 5), a contribution transferable to empirical research in general.

This contribution complements the existing literature in several ways. First, it bridges the gap between conceptual frameworks on systemic change and empirical measurement-methods. For example, socio-technical transition frameworks (e.g. Geels and Schot, 2007; McCormick et al., 2013; Vergragt et al., 2014), scenario planning techniques (e.g. Allwood et al., 2008; Carlsson et al., 2015; Schwark, 2009), and fore- and back-casting (e.g. Giurco et al., 2011; Robert, 2005; Vergragt and Quist, 2011) are used to model desired/assumed/planned transition pathways of technologies (e.g. regarding PSS dissemination), but such frameworks describing systemic change have been criticized for lacking clearly defined measurement-methods for empirical impact-assessments (e.g. Berkhout et al., 2004; Geels and Schot, 2007). In contrast, this article's discussion of generic time- and method-interdependencies of impact-assessments does not constitute a framework describing transition pathways of new technologies, yet it provides a conceptual base for the development of empirical research designs for applied impact-measurements. In the example of the PSS carsharing, conceptual frameworks on systemic change can be used to describe how carsharing generally morphs from a niche into the socio-technical landscape (analytical scope: society/country), whereas this article's analysis of generic methodological interdependencies when conceptualizing impacts as dynamic processes can be applied for empirical impact-evaluations of specific local carsharing-systems (analytical scope: single carsharing-scheme/single city).

Second, this article's analysis of generic time- and method-interdependencies when conceptualizing impacts as dynamic processes is transferable to empirical impact-measurements beyond carsharing. For example, the categorization of generic cross-sectional and longitudinal research designs combined with a cross-tabulation of target parameters and exemplary empirical impact-studies (Fig. 2) is applicable to structure *static* empirical impact-studies for any other sharing-based PSS (e.g. shared drilling tools). Furthermore, given that the proposed generic three-phase model of *dynamic* adaptation-processes (Fig. 3) links generic research designs to generic adaptation phases over time (based on the two central model-assumptions equilibrium-shift and user-turnover; see Section 3.2), the analysis of time- and method- interdependencies is applicable to conceptualize empirical impact-assessments for any product/service changing user-behavior *over time*. In addition, this article's final analytical step analyzing the applicability of generic research designs dependent on different generic states of environment-stability (Fig. 4) is e due to the consistent analysis on a generic level throughout the article e broadly generalizable to questions of causality analyzed with empirical research designs.

Third, the analysis of generic time- and method- interdependencies could be the missing link to unify the field of empirical carsharing impact-measurements. Until today, empirical carsharing-evaluations have used various different generic research designs (Section 3; Section 4) – even though the chosen measurement-method fundamentally determines the measured carsharing-impacts (Firnkorn, 2012; Martin and Shaheen, 2010). By clarifying that the current methodological disagreement regarding empirical measurements of hypothetical vs. retrospective impacts is more rhetoric than fundamental on a generic level (Section 4.1), this article may stimulate a methodological unification within the carsharing research field – which would allow policymakers to compare and generalize empirical carsharing-studies conducted in different cities. Given the consistent analysis on a generic level throughout this article, a methodological unification could also be stimulated by this article within non-carsharing research fields currently facing equally heterogeneous empirical impact-evaluations.

5.2. Contribution for policymakers

For policymakers, the proposed generic three-phase model of dynamic adaptation-processes (Fig. 3) could provide a new perspective on products/services changing user-behavior *over time* by replacing the question "What is the impact?" (=static view) with the question "What is the impact adaptation-process over time?" (=dynamic view). This article discussed the exemplary case of an impact initially developing towards the opposite of the long-term impact (Fig. 4) – for any new product/service with such an asymmetric impact-unfolding over time, policymakers should carefully reflect early static impact-snapshots as early impact-assessments might not be reliable indicators for long-term impacts. Given that long-term impact-quantifications are complex and difficult for all new products/services, the generic three-phase model (Fig. 3; Fig. 4) could provide a helpful thinking structure for policymakers to develop long-term oriented regulations for new technologies launched today (e.g. free-floating car/bike/scooter-sharing systems) or in the future (e.g. autonomous shared vehicle fleets) – in particular through an increased awareness that all *static* impact-snapshots can only reflect a transitory part of a larger and complex *dynamic* adaptation process over time.

The current shared-mobility expansion (Fig. 1) could make urban mobility orders of magnitude more resource-efficient compared to traditional private-car-usage, because collaborative consumption leverages impacts through a system-transformation beyond efficiency-improvements of individual private cars. However, the potential of shared-mobility systems to contribute to de-growth (Schneider et al., 2010; Sekulova et al., 2013; Videira et al., 2014) and sufficiency-strategies (Alcott, 2008; Figge et al., 2014; Princen, 2005) will only unfold with sufficient policy-support. For example, large-scale carsharing systems offering hundreds of shared vehicles per city only function when policymakers allow carsharing-providers to use public parking spaces (e.g. through agreements on annual parking flat rates payed per carsharing-vehicle). The proposed paradigm shift from a static to a dynamic view on carsharing-impacts (Fig. 3) could help policymakers to develop better carsharing-regulations based on a long-term perspective on the benefits for cities – which is particularly policy-relevant when initial short-term impact-evaluations point in the opposite direction of the long-term impacts (Fig. 4).

6. Future research

How can future research expand this article's idea to view carsharing-impacts *over time*? First, one-time vs. cumulative carsharing-effects could be distinguished. For example, a private car can only be abolished once, whereas the resulting VKT-reduction is ongoing (the colored areas in Fig. 4 illustrate a cumulative effect). Second, discounting-rules for future impacts could be defined given the infinite time-horizon in models describing impacts as open processes. Third, system-theories could be applied to explain carsharing-impacts dynamically, in particular theories conceptualizing impacts holistically as singular impulses, change-processes over time, and equilibrium-transformations. For example, thermodynamic principles have been used to explain the development of industries (Baldwin et al., 2004) and production-technologies (Li and Chai, 2007) *over time* – this approach could equally be used to explain carsharing-induced transformation-processes of the complex system city.

Future research expanding this article's analysis should ensure reciprocal learning among empirical studies on different PSS. Reviews of the PSS-field have repeatedly called for more quantitative research (Beuren et al., 2013; Boehm and Thomas, 2013; Mont and Tukker, 2006; Reim et al., 2014; Tukker, 2015), and the quantification of the PSS-field should involve a twofold exchange of methodological knowledge. First, across research-domains (e.g. business, engineering, informatics), given that PSS have historically "been basically independently discussed by researchers of different disciplines" (Boehm and Thomas, 2013, p. 245). Second, across PSS-cases (beyond carsharing), because all quantitative PSS-evaluations share similar methodological challenges. For instance, shared washing machines are a common PSS-example (Ceschin, 2013; Cook et al., 2012) – which *generic research design* (Fig. 2) should be used to quantify their impacts on material consumption? Shared power tools are another common PSS-example (Mont, 2004; Mylan, 2015) – should their impacts be conceptualized assuming an instant user-adaptation or an impact-unfolding over time (Fig. 3; Fig. 4; Fig. 5)? On an abstract level, all quantitative PSS-evaluations require the same generic methodological decisions, which creates a methodological synergy-potential.

The quantification of future research in the PSS field will be facilitated through technological progress. For example, the ubiquitous and real-time sensing of today's shared-mobility systems allows empirical impact-measurements with an unprecedented degree of precision, which could not be achieved by data generation methods just five years ago. However, more available data on new products/services is only useful if “Big Data” is accompanied by “Big Methodology” – more quantitative data requires more methodological knowledge and conceptual reflection on a generic level. For example, empirical carsharing-studies in the USA vs. China require the usage of different generic research designs due to different degrees of carsharing-relevant environment-stability (Section 4.2) – no matter how much quantitative data becomes available in both countries. Future empirical research should critically reflect on such fundamental methodological mechanisms before any impact-data is collected, to ensure correct and precise impacts-evaluations.

Does the world's accelerating technological change require a general paradigm shift towards a dynamic impact-view? Urban mobility has changed more during the current decade than in the previous century (Firnkorn and Müller, 2015), and today's carsharing-expansion (Fig. 1) is just one trend rapidly transforming cities worldwide. For example, environmentally friendly cars become new status symbols (Sexton and Sexton, 2014), automakers become integrated mobility-providers (e.g. www.moovel.com), private car owners become public drivers through smartphone-apps (e.g. *Uber*, *Sidecar*, *Lyft*), and autonomous cars become increasingly real (Burns, 2013). For any new product/service launched in a similarly unstable environment (Fig. 5), impacts must be evaluated with a dynamic view on processes of impacts unfolding over time.

Future research should not only explore the disruptive potential of shared-mobility systems in developed regions with a private motor-vehicle excess, but also in economically emerging countries. By 2030, humanity will need two earths to sustain its current lifestyle (Mont et al., 2014) – leapfrogging the era of *private* cars as the dominant transport mode in emerging countries would contribute to limiting global resource depletion (Africa leapfrogged the entire technological era of landlines through which the Western world went, and directly adopted mobile phones). Developed regions built around car-centric cities worldwide currently fight for a sustainable urban transformation (McCormick et al., 2013) – why should emerging countries not leapfrog the era of *private* cars and directly establish a culture of *shared* mobility from the beginning?

Conflicts of interest

The authors are free of conflicts of interest regarding this article.

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