Journal of Cleaner Production 145 (2017) 1–13

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Exploring policy impacts for servicising in product-based markets: A generic agent-based model

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ARTICLE INFO

Article history:
Received 17 December 2015
Received in revised form
2 January 2017
Accepted 3 January 2017
Available online 6 January 2017

Keywords:
Servicizing
Product-service systems
Absolute decoupling
Agent-based modelling
Behavioural economics
Policy exploration

ABSTRACT

The shift to markets based on servicising, i.e. market-level transitions from product-based to service-based production and consumption patterns, may contribute to achieve absolute decoupling, i.e. the combined development of economic growth and environmental impact reduction. However, the potential of this contribution is largely unknown. In this paper a generic agent-based model of servicising is presented with which this potential can be explored further, taking into account decision making procedures of business and consumer agents, including market research, preferences, and willingness to pay. The details of the servicising model are presented, and the model's abilities are demonstrated through three case studies from different sectors: car and bike sharing, crop protection, and domestic water-saving systems. Absolute decoupling was found to occur in some of the policy scenarios, but results vary widely between cases. It is concluded that the model can be used to explore the impact of public policy on the uptake of servicising and on absolute decoupling in various sectors, and is therefore a useful support tool for policy makers who aim to promote servicising, as well as for researchers studying potential servicising impacts.

1. Introduction

Continuous worldwide economic growth is still correlated with increasing consumption of resources and associated wastes, even though resource efficiency increases (Eurostat, 2011). However, to realise economies that remain within the environmental limits of our planet 'absolute decoupling' is needed, which stands for 'the situation in which resource impacts decline in absolute terms' (Jackson, 2011). Because economic growth is in itself an important societal objective as well, *absolute decoupling* is defined here as the combined development of economic growth and environmental impact reduction.

One concept that may contribute to achieving absolute decoupling is 'servicising' of the economy, i.e. the diffusion of product-service systems (PSSs) in industries and markets (Mont, 2004; Rothenberg, 2007). *Servicising* is defined as a market transaction that focuses on selling the function of products rather than the products themselves. Furthermore, a *servicising shift* is defined as a (macro-economic) market development where the share of services increases, both in terms of market share and in terms of the service component of offers.

Servicising could provide several benefits over traditional ownership-based consumption models. Economically, a more efficient use of resources must eventually translate to economic efficiency (Toffel, 2008). Socially, servicising can increase general quality of life (Devisscher and Mont, 2008). Environmentally, lower levels of resource extraction and waste production reduce the ecological footprint of production and consumption activities (Tukker and Jansen, 2006).

In view of its goal to make the European economy more sustainable, the European Commission is interested in exploring policies that may contribute to absolute decoupling, including policies that promote servicising (European Commission, 2012; European Environment Agency, 2012; Plepys et al., 2015). However, servicising shifts are complex social patterns that arise from dynamic interaction between buyers and sellers. Mont (2004) has identified the need for a methodology for the evaluation of servicising from

Abbreviations: ABM, agent-based modelling; CA, consuming agent; CB, Consuming Business; CM, Consumption Model; GWR, greywater recycling; IPM, integrated pest management; MM, Manufacturing Model; PB, Producing Business; RWH, rainwater harvesting; SM, Sales Model.

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http://dx.doi.org/10.1016/j.jclepro.2017.01.016
0959-6526/

environmental, economic and social perspectives. Previous modelling efforts have taken a business development perspective and/or stayed on the operational and organisational level (Beuren et al., 2013; Bianchi et al., 2009; Tukker, 2015), whereas the simulation of servicising shifts requires the consideration of both business and consumer behaviour, as well as a system-level perspective.

In this paper the following research question is answered: *How can the potential impact of servicising policy on absolute decoupling be explored by means of agent-based modelling, and how can policy makers and researchers be supported in the modelling process*? This question is addressed by means of the description and demonstration of a generic agent-based model that policy makers can use to explore the impacts of servicising policy in markets from various domains. This model is to our knowledge the first comprehensive simulation model dealing with the service economy. The model mechanisms are described using a narrative approach, and the model's functionality is illustrated through three servicising case studies. Furthermore, the practical value and limitations of the model are discussed.

2. Agent-based modelling literature

Agent-based modelling (ABM) is one of the few suitable tools to capture heterogeneity, relationships between individual actors, and non-rational preferences and behaviour in a single methodology (Maidstone, 2012). ABM simulates system behaviour as the emergent result of the (inter)actions of individuals and organisations, represented as autonomous agents. This makes this methodology very suitable for the analysis of complex adaptive systems such as economies, where local economic interactions influence macroeconomic regularities which in turn influence future interactions (Tesfatsion, 2003), and for the analysis of public policy impacts on the behaviour of social and economic actors (Lempert, 2002).

In the context of servicising shifts, ABM enables the investigation of production and consumption patterns on a system level, based on assumptions on the heterogeneous properties, motivations and behaviour of individual businesses and consumers. It thereby provides a valuable tool to explore economic, social and environmental effects of servicising policy in a quantitative way.

Agent-based models of servicising, or the service economy, are scarce in academic literature. Desmarchelier et al. (2013) have developed a model of eco-innovation in services, but the business agent decision making focuses on product design. Rajapakse and Terano (2013) present a model of service ecosystems, but here the decision making focuses on the co-creation of value by both businesses and consumers, not so much on the emerging market-level outcomes.

Although many academics have studied artificial markets, most of the developed models concentrate on a limited number of aspects of artificial markets. For instance, such studies may focus on consumer choice processes (e.g., Eppstein et al. (2011); Mueller and De Haan (2009); Zhang and Zhang (2007)), or on the role of social networks in the diffusion of innovations (e.g., Kiesling et al. (2012); Laciana and Oteiza-Aguirre (2014); Neri (2007)). While providing important insight in key market mechanisms, such approaches do not allow for an exploration of dynamic interaction between sellers and buyers. Such interaction is understood to be an important dynamic in servicising shifts (Mont, 2002).

Published studies present various conceptualisations of business model development. In one possible approach, business agents incrementally improve certain aspects of their output product, typically based on genetic algorithms (e.g., Janssen and Jager (2002); Ng (2008)). A more common approach is to let business agents choose from a fixed set of products. In most studies, business agents either consider products or services.

Furthermore, artificial market models feature various price-setting mechanisms, e.g. fixed prices, a mark-up or multiplier on marginal cost (Chang et al., 2008; Dosi et al., 2009; Lengnick, 2013; Zhang et al., 2011), incremental periodical price adjustments of a fixed size (Ogibayashi and Takashima, 2009), or pricing based on evolutionary learning (Itoh et al., 2006; Liu et al., 2010). Consumer demand is often not considered within these pricing mechanisms. If the business agents collect information about the demand of consumer agents, price setting can become more accurate and realistic, but also more complex.

Moving on to consumer-side logic, existing literature considers many different mechanisms that people and organisations may use to choose between offers on a market. Consumers may just use simple heuristics such as repetition or imitation (Maya Sopha et al., 2011). Alternatively, they may choose the product with the best score on their favourite attribute (Schwarz and Ernst, 2009) or apply weights on all scores, resulting in additive utility scores for each offer (Afman et al., 2010; Chappin et al., 2007). Choi et al. (2012) and Eppstein et al. (2011) add a filtering step, where products not meeting certain thresholds are discarded before proceeding with a second round of comparison.

Finally, the heterogeneity of individuals and businesses can influence market outcomes in unpredictable ways. Such heterogeneity is represented by differences in the attributes of individual agents. In de Haan et al. (2009) and Choi et al. (2012), sociodemographic attributes of consumer agents play a role in their choice between various car types, and therefore also influence the effectiveness of policy measures. In a large-scale agent-based simulation of the European economy, Deissenberg et al. (2008) find that ‘even starting with almost identical initial conditions in the two regions, the emerging heterogeneity among agents may lead, after an unpredictable time, to a stark differentiation between the regional economies’.

The servicising model presented in this paper incorporates the following conceptualisation of a market:

- The model captures interactive decision making processes of both sellers (i.e., producers) and buyers (i.e., consumers).
- Business agents can consider both product-based and service-based business models, and may provide a product and a service at the same time (based on the same input product).
- The model allows for large changes of production and consumption patterns, as agents switch between available business models and product/service offers.
- It includes a sophisticated price-setting mechanism based on market research by business agents, which enables them to adapt to the demand of consumer agents.
- The model combines the additive utility approach with threshold filtering, while also taking budget constraints into account, which resembles the approach in Eppstein et al. (2011).
- It offers a very flexible parametrisation of heterogeneous properties of market participants, with variation between and within groups. The model thus allows for a detailed representation of both the variety and the clustering of agent preferences that characterise real-world markets.

3. Model description

We have developed a generic agent-based model of servicising in the frame of the European FP7 project ‘Servicising Policy for a Resource Efficient Economy (SPREE)’.[2] Three sector case studies

[2] http://www.spreeproject.com/, accessed on 26 July 2016.

have been studied in the project using this servicising model: car and bike sharing, crop protection against pests and diseases, and domestic greywater recycling and rainwater harvesting systems.

The model has been implemented in NetLogo, an open-source platform for building agent-based models[3] (Wilensky and Rand, 2015). The servicising model can be downloaded from the SPREE wiki,[4] and from OpenABM.[5]

3.1. Model structure

The model structure has been developed in the form of a conceptual model of servicising, which formed the first main modelling step in the project. The conceptual model describes the agents and objects relevant to servicising. The main model structure is presented here. More details, including a full description of the agent/object properties, are given in Kisjes (2014) and van der Veen et al. (Unpublished results).

The agents, objects and the relations between them are illustrated in Fig. 1.

3.1.1. Market definition

The model represents a single market of autonomous sellers and buyers, centred around a single consumption need. This need can be satisfied through competing *Products* and *Services*. The *Producing Business (PB)* represents the seller, and the *Consuming Business (CB)* and/or the *Consumer* represents the buyer. 'Consuming agent' (CA) is used as an overarching term for CBs and Consumers. Different consuming agent groups have different needs and preferences, representing different lifestyles.

3.1.2. Contracts and resources

Services are delivered through *Service Contracts* between PBs and the consuming agents. The Products and Services have certain amounts of *Resource* types associated with them. Resources are used in the servicising model to facilitate the accounting of resource extraction and emission and waste generation taking place throughout the supply chain. They can also be used to represent life-cycle assessment (LCA) impact categories such as terrestrial acidification and ozone depletion.

3.1.3. Transformation models

Products and Services are produced and consumed through three types of 'transformation models': *Manufacturing Models (MMs)*, *Sales Models (SMs)* and *Consumption Models (CMs)*. Producing Businesses repeatedly configure their 'business model', which consists of one MM and one or two SMs that can be periodically replaced. Each MM allows a Producing Business to procure a particular (primary) Product type, either by producing it in-house or buying it off-the-shelve. Each Sales Model then represents one possible way to offer a specific Product or Service type to consuming agents in the market. The outputs of all active SMs on the market together make up the range of Products and Services that CAs may choose from in order to satisfy their need. CMs define how CAs can satisfy their need through a specific Product or Service. All available transformation models are predefined in the input data, but the effective chains of manufacturing, sales and consumption follow dynamically from simulated choices and interactions.

[3] https://ccl.northwestern.edu/netlogo/, accessed on 26 July 2016.

[4] http://www.wiki.spreeproject.com/index.php?title=SPREE_agent-based_model, accessed on 26 July 2016. The wiki has been developed and maintained over the course of the project, from July 2012 to June 2015.

[5] https://www.openabm.org/model/4704/, accessed on 25 July 2016.

3.1.4. Infrastructures, skills and external markets

Agents may require access to certain *Infrastructures* and/or possession of certain *Skills* in order to adopt a certain MM, SM or CM. Upstream inputs for the transformation models originate from the *World Market*, which also accepts obsolete Products. World Market prices are assumed independent of the dynamics of the focal market. Outputs can also be disposed in the *Physical Environment*.

3.1.5. External influences

Furthermore, the simulated market can be influenced externally by *Policy Instruments* and *Market Developments*. The Policy Instruments represent concrete regulatory measures that influence the market, such as a subsidy. The model allows considerable freedom to define how elements and values in the model are affected by a specific Policy Instrument. This is supported by the External Effect object, which defines a detailed effect on an agent/object property, and by two supporting objects that enable the selection of specific agent/object classes or instances. In addition, Policy Instruments may activate and deactivate based on pre-configured conditions, which are evaluated at each time step. For instance, a subsidy may start at 'x' number of days since the start of the simulation and then deactivate once the subsidised technology has conquered market share 'y'. Market Developments may represent specific external, non-regulatory developments that influence the simulated market, such as a technological development or a price decrease in the World Market. They work in the same way as Policy Instruments.

Policy Instruments in the servicising model are usually not evaluated in isolation. Policy Packages represent coherent sets of Policy Instruments that require, complement or reinforce each other to have optimal effect (Givoni et al., 2013). The servicising model can then be used to explore the effects of alternative Policy Packages. Similar to the way Policy Instruments group into Policy Packages, Market Developments together constitute Market Scenarios. One Market Scenario represents one possible set of future developments that will affect the simulated market.

3.2. Assumptions

The model includes many assumptions that define the scope and nature of model elements, actions and decision making processes, which cannot be changed by the modeller. Here the most important assumptions are summed up. The complete list of model assumptions can be found in the Supplementary material, including a rationale.

- The model can only be used to define and simulate servicising cases that involve businesses, i.e. no consumer-to-consumer cases.
- There is no spatial or network representation in the model.
- A single market of buyers and sellers is modelled, i.e. a single supply chain link.
- Consuming agents have a single functional need, e.g. a need for transportation. The magnitude of the need per time unit is fixed.
- There is a fixed number of consuming agents in the simulation.
- Consuming agents choose the best offer available, considering both cost and 'preference fit'.[6]
- CAs can adopt one Product/Service at a time.

[6] The preference fit indicates how well a Product or Service scores on the preferences of a consuming agent. Its contribution to the overall utility of a Product or Service for a CA is described in the Supplementary material.

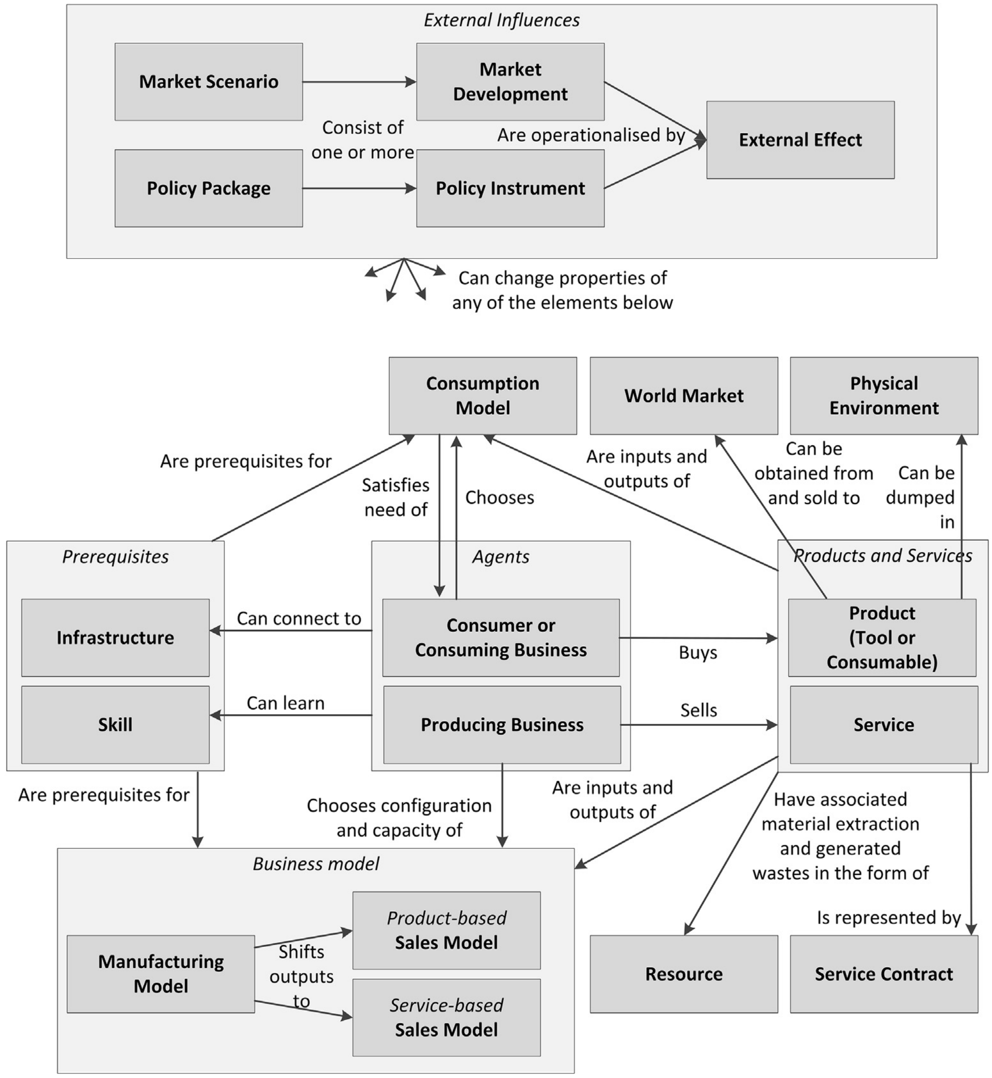

Fig. 1. Overview of the structure of agents and objects in the servicing model (adapted from Kisjes (2014)).

- Producing Businesses choose a business model and offer prices that lead to the highest expected profit.
- PBs can adopt one business model at a time. As a result, they cannot produce more than one Product and one Service at a time (which must be based on the same main input Product).
- Producing Business can leave and re-enter the market, but there is a maximum number of PBs that can be active.
- PBs have limited information on consumer demand, i.e. they only obtain information from a subset of CAs.
- No agent learning takes place, i.e. agents do not consider results of previous rounds.
- The set of Products and Services that may be delivered and used is predefined.

3.3. Narrative

The model mechanisms are explained in a ‘narrative’ format, which research suggests are more easily read, understood and recalled than a logical-scientific format (Dahlstrom, 2014). Also, agent-based models essentially formalise ‘which agent does what with whom and when’, and narratives are well suited to capture this (van Dam et al., 2012). In the narrative, we try to picture ourselves as one of the agents in the model and describe the events we encounter, and the actions we may take, in each time step in the simulation. Traditionally, the agent starts by waking up in the morning and having a cup of coffee, and moves on from there. Given that the servicing model features two distinctive types of agents, a separate narrative is needed for both. A fully formalised description of the mechanisms is provided in the Supplementary material.

3.3.1. Consuming agent narrative

The consuming agent wakes up in the morning, has a cup of coffee and checks on her calendar whether it is already time to reflect on the way things are going for her. Of course, she has already adopted a Consumption Model to be able to structurally satisfy her daily (or weekly, monthly, etc.) need, and has chosen a regular supplier who made a good offer the last time around.

But every now and then, she wants to make sure that she is not being played for a fool and looks around for cheaper suppliers (although there must be a substantial difference to make up for the hassle of switching). This is easy enough, because all market prices are public information. If there is a better supplier for the Service she is receiving, she will break her contract and sign a new one with that supplier. If she is using a Product, she will consider if it is not cheaper to switch than to continue using her Product until it is at end of life.

At some rare times, she feels ready to change her consumption behaviour. If that is the case, she performs a thorough evaluation of all the offers on the market, intuitively applying her weights and thresholds for qualitative properties of the offer. She then compares the offers one-by-one, keeping track of (and comparing with) the best offer encountered so far. Some offers may be a better fit to her lifestyle, but only to a certain extent is she prepared to pay for a better fit. Offers that exceed her budget (taking into account depreciation and operating costs) will never be selected. Although ready for switching, the agent is still a creature of habit, so offers that match her current supplier and/or consumption model receive a bonus in their evaluation. If the offer that comes out on top differs from the offer currently used, she will switch. If necessary, she sells or dumps any remaining Products, and adopts the Consumption Model that corresponds to the chosen Product or Service.

Finally, the agent routinely refills her current Product stock, and consumes the amount of it needed to fulfil her periodic need.

3.3.2. Producing Business narrative

The story of the Producing Business is very similar to that of the CA, but she has a little more work to do. Naturally, after waking up in the morning, she first enjoys a fresh cup of coffee. At some fixed intervals, the business agent will re-evaluate whether her current selling price still maximises her profit. After all, one should always keep an eye on the competition. To make this assessment, she asks a fraction of the CAs to participate in a brief survey and state the maximum price they are prepared to pay for the current offer(s) of the PB. Being computer agents, they are all happy to cooperate without lying. This allows the PB to construct a price-demand curve and calculate the price that is expected to generate the highest profit over a predefined horizon. She then updates her offer price and production rate accordingly.

Less frequently than the selling price reconsideration, the PB performs a reality check to see if her current business model is still (the most) viable. The business model allows her to transform inputs from the World Market into Products and/or Services that can be sold to CAs. She can choose between different main inputs, but also between transforming the main input into a Product offer, a Service offer, or both. For every possible business model configuration she carries out the same market research procedure as described above, asking a subset of CAs at what price they would switch to the hypothetical new offer. This exercise results in an optimal price and associated sales volume. In addition, the PB calculates the costs of all required investments (including costs of new Skills and Infrastructures). This leads to an average expected profit over a certain predefined 'consideration period' (e.g. 5 years). She then 'calculates' to what extent the business model fits her strategic preferences, defined in terms of weights and thresholds. She is willing to sacrifice some profit for a better strategic fit, but not too much! This routine reveals which business model is most desirable to the PB. If that model differs from the currently adopted model, she will make the switch and invest in the new business model. Her current customers must immediately choose a new supplier, but may decide to switch to the new offer in a future reconsideration routine.

Furthermore, the PB continues to do what she does best: buying inputs from the World Market, transforming them into Products and/or Services, selling those to her customers, and disposing of secondary outputs.

3.4. Data input

In essence, the data input for the servicising model consists of the various classes (types) of agents and objects that are part of a particular servicising case, and the property values of each of the agent and object classes. In a nutshell, the modeller defines the following:

- The monetary unit, basic time unit (the time period represented by one time step in the model), and the unit in which the consuming agent's need is expressed.
- The list of preferences that the agents consider (e.g., status, comfort, and environmental friendliness).
- The behavioural settings of different consuming agent and Producing Business agent types, including willingness to pay, preference weights and minimum thresholds, return-on-investment period, and the period after which the agent reconsiders available options.
- The preference scores and associated resources and wastes of Products and Services.
- The environmental impact categories represented by the Resource types.
- The material inputs and outputs, conversion rates and costs of Manufacturing Models, Sales Models, and Consumption Models.
- The prerequisite Infrastructures and Skills, World Market prices and dumping costs.
- The activation conditions and effects of Policy Instruments and Market Developments.
- Policy Packages and Market Scenarios.

Many of the data inputs can be collected empirically, through desk studies, consumer questionnaires and business interviews. However, for unavailable data and data format conversions, some estimations will be needed. This is especially true for the specific Policy Instrument effects, which are often unknown. Here, modellers must rely on expert opinions, perform sensitivity analyses to test the robustness of results, and be cautious in drawing conclusions.

We have developed an Excel spreadsheet in which the input data can be entered. The spreadsheet describes in detail what data are needed in what format in order to fully represent a servicising case in the agent-based model.

3.5. Data output

The servicising model enables an exploratory analysis of the potential impact of servicising on three different dimensions: economic, environmental and social. In this section, the metrics that are used to capture the simulation results are briefly discussed for each dimension.

3.5.1. Economic effects

The economic outputs provide answers to three questions: Which Products and Services become dominant in a certain scenario, how does this affect business profitability, and what does it mean for consumer expenditure? The relative dominance of Products and Services is easily captured by market shares throughout the simulated period. The 'servicising rate' (i.e., the aggregate market share of Services) represents the degree of servicising in the market. To assess business profitability and consumer expenditures, all revenues and expenditures made by agents are tracked. The resulting cash balances provide insight in the economic effects of a Policy Instrument or Market Development on both types of agents. Two more economic outputs are the average Product and Service prices that PBs specify based on their market research procedures, and the total number of Product and Service units that are used during the simulated period. Finally, the model keeps track of the total market revenue of Producing Businesses over time, the 'supply chain GDP'.

3.5.2. Environmental effects

During each time step, the model calculates the total, system-level environmental impacts associated with that time step in a bottom-up way, based on the Products and Services in use at the time, and their associated impacts. The impacts per Product or Service (i.e., LCA data) are not calculated by the model, but are part of the required input data. Because the model focuses on one segment in the supply chain, LCA impacts per product or service unit can be assessed and entered a priori. The supply chain GDP and the environmental impacts together form the model indicator for absolute decoupling.

3.5.3. Social effects

The 'lifestyle fit' indicates how satisfied consumers are with the Products and Services they adopt. It is quantified by calculating the degree to which the Consumption Models selected by the CAs meet their preferences. If the average lifestyle fit increases over the course of the simulation, this indicates that consuming agents have gained access to ways of consumption that better fit their lifestyle. The model also keeps track of the expenditure of time and money for all consuming agents over the course of the simulation. Downward trends on these metrics indicate that consumers free up resources that could be used to pursue other life-fulfilling activities. Any potential rebound effects (Sorrell and Dimitropoulos, 2008) associated with those additional activities are not included in the model.

3.6. Modelling process

The servicising model has been developed as a generic model, which is suitable for formalisation and simulation of servicising cases in various sectors. The model takes away a large part of the complexity of the modelling process, so that the modeller can focus on the definition and model specification of the servicising case.

To start up the modelling process for a new case study, the modeller should first of all define the case, by specifying the central need that is fulfilled, the functional unit, the servicising shift of interest, the geographical boundary, and the basic time unit. The next step is to formalise the case study in terms of agents and object classes: which categories of agents can defined, what are the most relevant and interesting Products and Services, etc. The third step is to collect and enter input data for all attributes of all model element classes in the generic Excel input spreadsheet. To obtain case-specific data, cooperation with domain experts is highly recommendable. The Excel sheet enables an automated generation of text files that can be read by NetLogo, and can be selected in the NetLogo interface.

For the model experimentation step, the modeller must formulate hypotheses, scenarios and the scenario space (van Dam et al., 2012). This involves decisions on which alternative input data sets to run (which can be represented by different text files), which policy and market development scenarios to run, how many runs to carry out per scenario, and how many time ticks per run. The number of ticks should be large enough to allow for sufficient strategic reconsiderations by the agents. Especially if simulation results vary widely between runs, it is important to perform a high number of runs, and to show not only the average value but also e.g. the standard deviation of output variables.

To automate the experiments, the use of a simulation environment and script is recommended. Within the project, we have used 'R' for this purpose,[7] and the package 'RNetLogo' to enable the operation of NetLogo through R (Thiele et al., 2012; Thiele, 2014).

The following step is data analysis, which includes data exploration, pattern identification and interpretation, and experiment iteration (van Dam et al., 2012). To study the impacts of various policies on absolute decoupling, the modeller should compare the supply-chain GDP and environmental impact results of the base case scenario (i.e. no active Policy Instruments) with policy scenario results. The inclusion of different input data sets as part of a sensitivity analysis will bring further insights and higher confidence in the conclusions that are drawn from the simulation study.

4. Model demonstration

In this section the expressiveness of the generic servicising model is demonstrated by means of three case studies: car and bike sharing, crop protection, and domestic water-saving systems. For each case, a short description is provided, followed by an illustration of the various simulation results obtained.[8]

4.1. Car and bike sharing

The case of car and bike sharing is a business-to-consumer case, where the Producing Business agents are car retailers, and the Consumer agents are individuals who have a need for transport within the geographical boundaries of a city (measured in kilometres per week). The considered region is London city, so input data has been collected for this region. In this case Producing Business can only consider business models related to car and bike sharing. Consumers can choose between car and bike sharing Services, car and bike Products, and a public transport Service. This case formalisation allows for a transparent evaluation of the viability of car and bike sharing business models: PB agents will only stay within the market if they expect to make a profit with car sharing or bike sharing. Similarly, a PB will only obtain a certain share of the 'transportation market' if a share of the Consumers considers her service offer to be best.

In Fig. 2, a selection of simulation results of the mobility case is shown. Depicted are four main output variables, for three different scenarios. In the 'base case' scenario, the simulation has been run without any active Policy Instrument or Policy Package. Policy Package C includes instruments promoting bicycle use and bicycle sharing, which is represented by higher preference scores for the bicycle Product and the bicycle sharing Service. Policy Package D includes instruments that promote car sharing, which involves lower costs and higher preference scores for car sharing Services.

Each scenario has been run 100 times, for a duration of 100 time ticks (weeks) each. This allowed the agents to reconsider their business model or consumption model multiple times during the simulation. It can be observed that the results are quite consistent, despite the random factors in the simulation.[9] Strong changes in the early phase for some of the outputs indicate large dynamics in agents' choices as the market develops from its initial state.[10] Here,

[7] https://www.r-project.org/, accessed on 18 July 2016.

[8] In the SPREE project, an extensive simulation has been carried out for the sector cases. Also, other country cases have been simulated as part of a cross-country analysis. The simulation results have been used as an input for servicising policy package formulation and analysis (Akyelken et al., 2015; López-Avilés et al., 2015; Pereira et al., 2015).

[9] This includes the order of actions by agents, the consumer subset ending up in the market research procedure, and the initialisation of Consumer needs, agent reconsideration times and remaining use time of Tools during the model setup.

[10] The PBs start out with an initial business model, which is part of the model input, and Consumers choose a first offer from the initially available ones. When PBs change their business model for the first time, it is based on the actual state of the market, which may bring PBs and Consumers to choose different business models and offers, respectively.

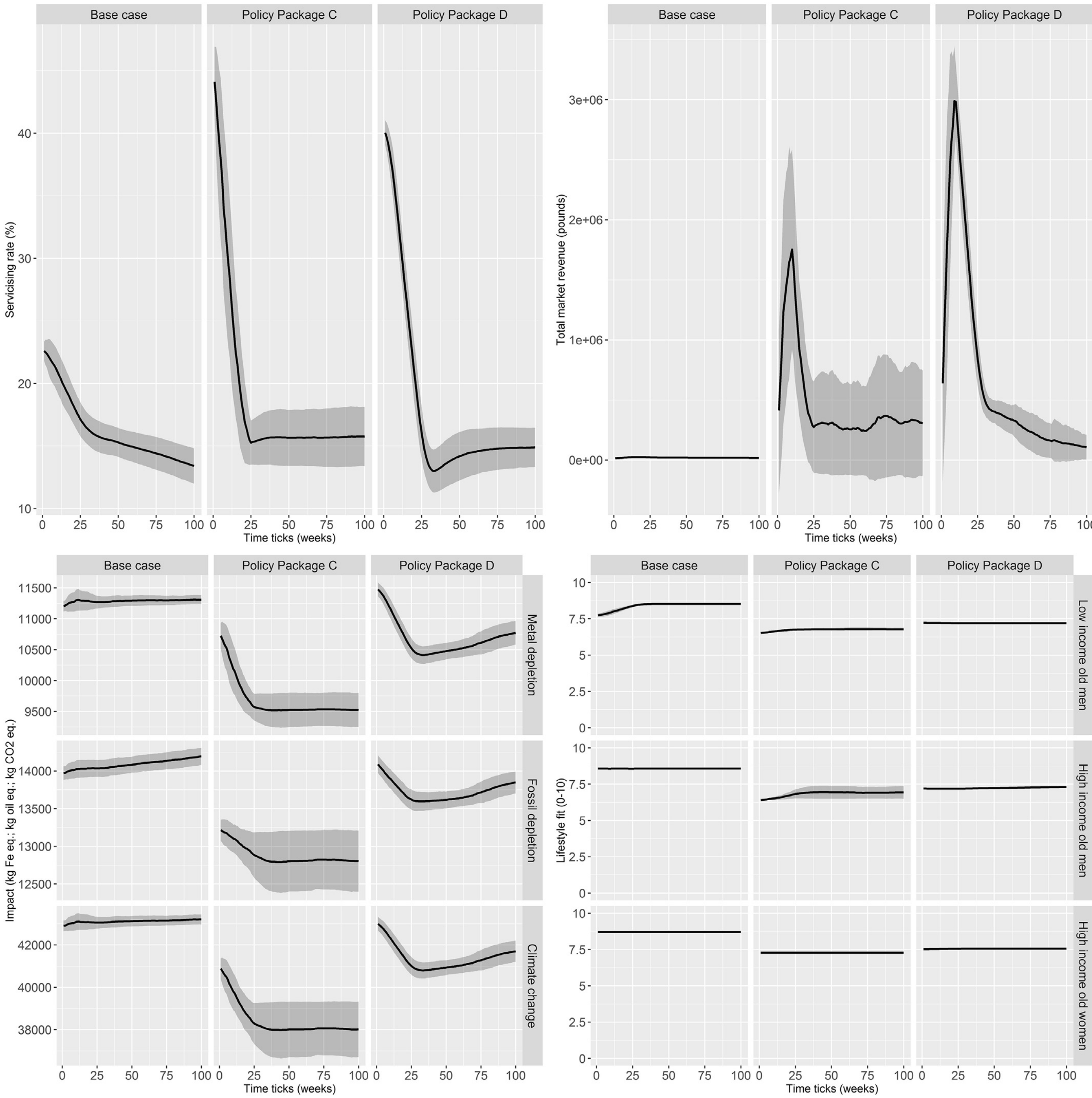

Fig. 2. Example simulation results from the mobility case: servicising rate (top left), supply chain GDP (top right), system-level environmental impacts (bottom left), and Consumer lifestyle fit (bottom right). The lines represent the average value of the runs, and the borders of the bands indicate the standard deviation.

the attractive initial car sharing offers turned out to be unprofitable, causing a reduction of the servicising rate over time.

Comparing the different scenarios, a first observation that can be made from Fig. 2 is that neither of the policy scenarios does much to increase the servicising rate, i.e. the aggregate market share of services. Although both Policy Packages do establish a servicising rate of roughly 15%, this is mainly caused by a higher use of the public transport Service. Thus, the packages were found to be ineffective in promoting car or bike sharing. Consumers are cheaper off in the long run when buying their own car or bike. In the base case, Consumers do not opt for car or bike sharing at all and PBs leave the market, which is why the supply chain GDP (which reflects the total revenue of the PBs combined) remains zero. In both policy scenarios, the supply chain GDP is soaring, because the PBs are initially faced with high car sharing sales increases (from virtually zero to more than 250,000 pounds/week for package C and more than 100,000 pounds/week for package D[11]). Furthermore, it can be seen that the environmental impacts are lower, by

[11] It must be remarked here that the number of Consumers in the model is 1,000, which comes down to 250 and 100 pounds/week per Consumer for each of the packages.

more than 10% for package C, and by a couple of percentages for package D, which reflects the lower impacts of public transport.

Combining the results on supply chain GDP and environmental impact, it can be observed that absolute decoupling emerges when either of the Policy Packages is implemented, but this is not because of an increasing adoption of car or bike sharing. Finally, we can observe a slight reduction in the average lifestyle fit (see Section 3.5). This indicates that the public transport service has a lower preference fit than owned car products.

Within the project, a total of 14 individual Policy Instruments and 9 Policy Packages have been simulated for the car and bike sharing case (Akyelken et al., 2015). In general, these were not very effective in increasing the uptake of car or bike sharing. Because it was assumed for this case that the number of kilometres the cars are used before they are at end of life is not influenced by car sharing, a higher uptake of car sharing led to similar environmental impacts. Absolute decoupling was found for some policy scenarios in which the use of public transport increased.

4.2. Crop protection

This servicising case is a business-to-business case, where the Producing Businesses represent pesticide retailers, who provide pest protection Products and Services to Consuming Businesses that represent farmers. The considered case, for which input data has been collected, is grape cultivation in Galicia, Spain. The model-specific definition of this case includes four Products and Services that agents can choose between: a conventional pesticides package Product, a corresponding pesticide service, an integrated pest management (IPM) package Product, and a corresponding IPM Service. The idea behind IPM is that protection against pests and diseases is carried out in an integrated fashion, and is attuned to the farmer's situation. The CBs (farmers) have a need for crop protection, measured in hectares per season (year).

In Fig. 3, a selection of simulation results of the agri-food case is shown, for three scenarios: the base case, a scenario in which Policy Instrument 5 was active, and a scenario that applied Policy Instrument 30. Policy Instrument 5 represents a subsidy for collective hiring of external services, and the defined direct policy effect is a reduction of variable costs of the Consumption Model corresponding to the IPM Service of 800 euro per hectare per season. Policy Instrument 30 represents an environmental awareness campaign, which increases the ‘environmental profile’ preference weight of all CBs by 3 (with the maximum being 5).

It can be seen that both Policy Instruments cause a large shift in the market from pesticide Package to IPM Service. The effect is much larger for instrument 5 than for instrument 30, however: The IPM Service share reaches over 80% for instrument 5 compared to over 40% for instrument 30 (with about 7% in the base case). Thus, in this case study even single instruments are shown to highly promote servicising. Also, the subsidy proves twice as effective as the environmental awareness campaign. Furthermore, instrument 5 leads to an increase in supply chain GDP of about 40%, against 17% for instrument 30. This reflects that the higher costs for the PBs are distributed to the CBs, increasing the revenues of the PB. However, the PB profit results show that profit levels remain about the same. This is because the level of competition between the PBs, which keeps profit margins low, does not differ across the scenarios. Finally, an interesting outcome is that the profits of the Consuming Businesses have declined compared to the base case, despite the increase in revenue that they obtain from the shift to IPM service. This is because the higher crop protection costs outweigh the revenue increase.

Within the project, a total of 9 individual Policy Instruments and 8 Policy Packages have been simulated for the crop protection case. In general, these were very effective in increasing the uptake of the IPM service, thereby substantially decreasing environmental impacts (Pereira et al., 2015). Absolute decoupling was found for a few Policy Instruments, including instruments 5 and 30 (but is more profound in case of instrument 5, i.e. the subsidy), and for all of the Policy Packages.

4.3. Domestic water-saving systems

The case study of domestic water savings systems is another business-to-consumer case, which concerns the possible servicising of domestic greywater recycling and rainwater harvesting systems. The region considered is in the south-east of England. The Producing Businesses represent providers of water-saving system products and/or services. The Consumers represent individual households who need water for various domestic uses. Having a water-saving system in their house may bring down their water bill, and obtaining this as a service (with the PB owning and maintaining the system) can prevent high upfront investment costs and maintenance costs. The main options that the agents have are the product and service versions of a small greywater recycling (GWR) system, and a large combined GWR and rainwater harvesting (RWH) system. Importantly, Consumers can also opt for a ‘no offer’ Consumption model, and just purchase potable water from the World Market (which is modelled as a secondary input of the CMs). Also, a distinction is made between Consumer groups (classes) with and without a water meter (which reflects the actual situation in the UK). Non-metered Consumers pay a fixed yearly water bill. The basic time unit (model time step) for this case is a year.

In Fig. 4, a selection of simulation results of the water case is shown. Next to the base case results, the results of Policy Instrument 6 and Policy Instrument 9 are shown. Instrument 6 represents the implementation of universal water metering, and establishes that all non-metered Consumers get access to the water meter Infrastructure, implying that all Consumers will pay per litre of consumed potable water. Instrument 9 represents an extensive promotion program for GWR and RWH systems that is targeted to both consumers and businesses. Its defined direct effects include a 20% increase of the willingness to pay for preference fit of all Consumers, an increase of the ‘environmental values’ preference weight of all Consumers by 1 (with a maximum of 5), an increase of the ‘flexibility of market contract’ and ‘market positioning’ preferences weights of all PBs by 1, and a reduction of the risk aversion factor of PBs by 10%.

Both Policy Instruments lead to a similar, significant increase of the servicising rate. However, instrument 6 (universal water metering) causes a much larger increase in the market share of the large combined GWR & RWH system service than instrument 9 (the promotion program), which does not substantially change the market shares of both system services compared to the base case. Apparently, the shift to volumetric water billing makes the large combined system more attractive to Consumers, because of a larger reduction in annual water consumption. Also, it appears that this instrument may be more effective in promoting servicising than the GWR & RWH promotion program.[12] The two environmental impacts included in this case are CO_2 emissions and water consumption. It can be observed that instrument 6 leads to a large reduction of CO_2 emissions whereas instrument 9 has no noticeable effect. This reflects that the large combined system results in larger decreases in potable water consumption than the small GWR

[12] In addition, the behavioural effects of promotion policies are arguably less certain to develop in actuality than those of universal water metering.

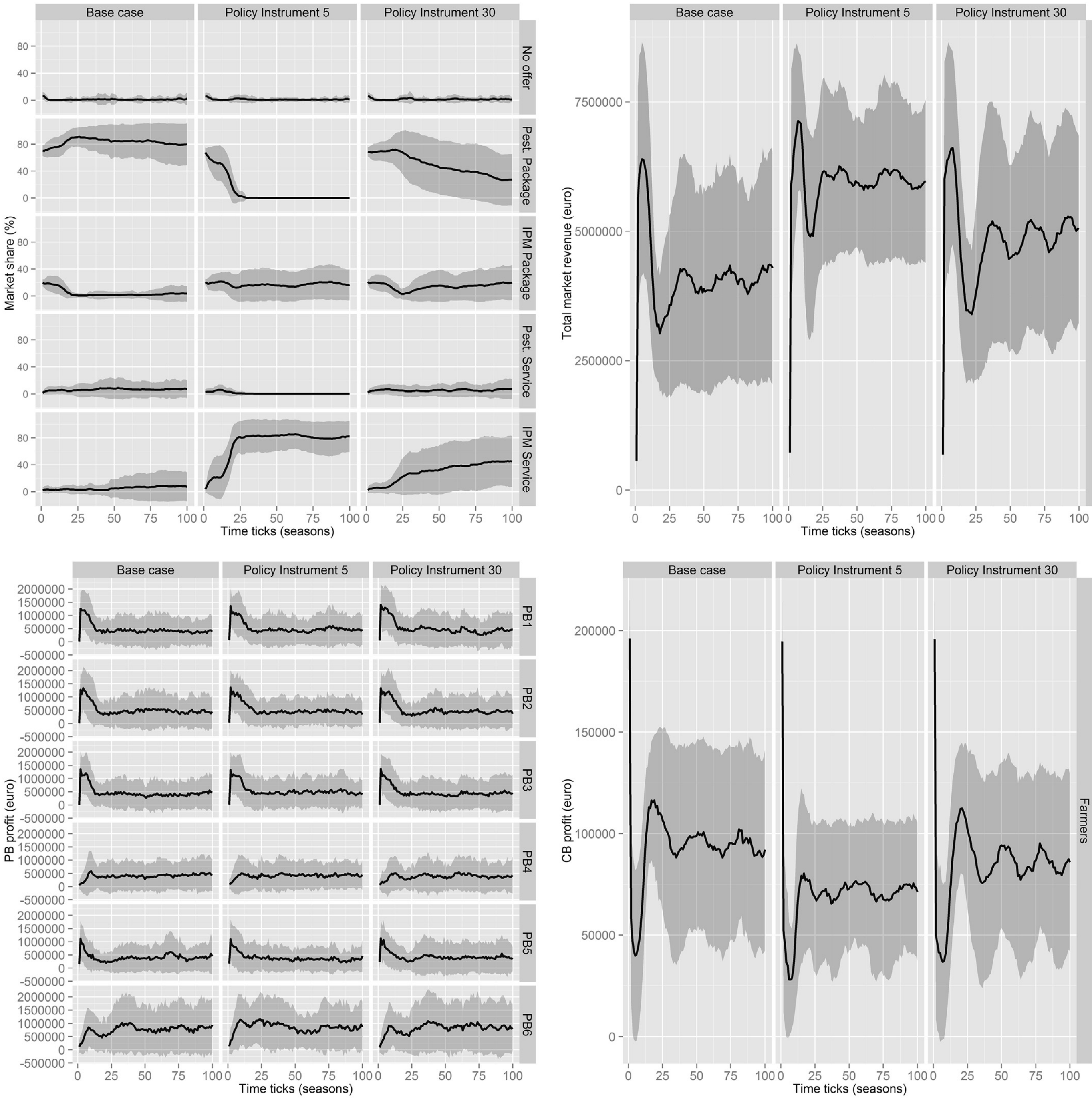

Fig. 3. Example simulation results from the agri-food case: Product/Service market shares (top left), supply chain GDP (top right), PB profit (bottom left), and CB profit (bottom right). The lines represent the average value of the runs, and the borders of the bands indicate the standard deviation.

system, reducing the CO_2 emissions related to abstracting, cleaning and distributing potable water. It also means that the positive impact of the lower water use on CO_2 emissions outweighs the negative impact related to the production of a larger system. Finally, some shift in water consumption patterns can be seen for different Consumer groups. These reflect their changes in Product/Service consumption. Under instrument 6 many more agents from the prosperous family Consumer groups adopt the large GWR & RWH system service, causing an overall reduction in water consumption.

Within the project, a total of 14 individual Policy Instruments and 24 Policy Packages have been simulated for the water-saving systems case. In general, these were very effective in increasing the uptake of servicising, thereby substantially reducing CO_2 emissions and water consumption (López-Avilés et al., 2015). Absolute decoupling was found for many Policy Instruments and most Policy Packages, but not for instruments 6 and 9. Environmental impacts dropped due to universal water metering (instrument 6), but supply-chain GDP did not rise. The promotion program (instrument 9) did not have a noticeable effect on either of the outputs.

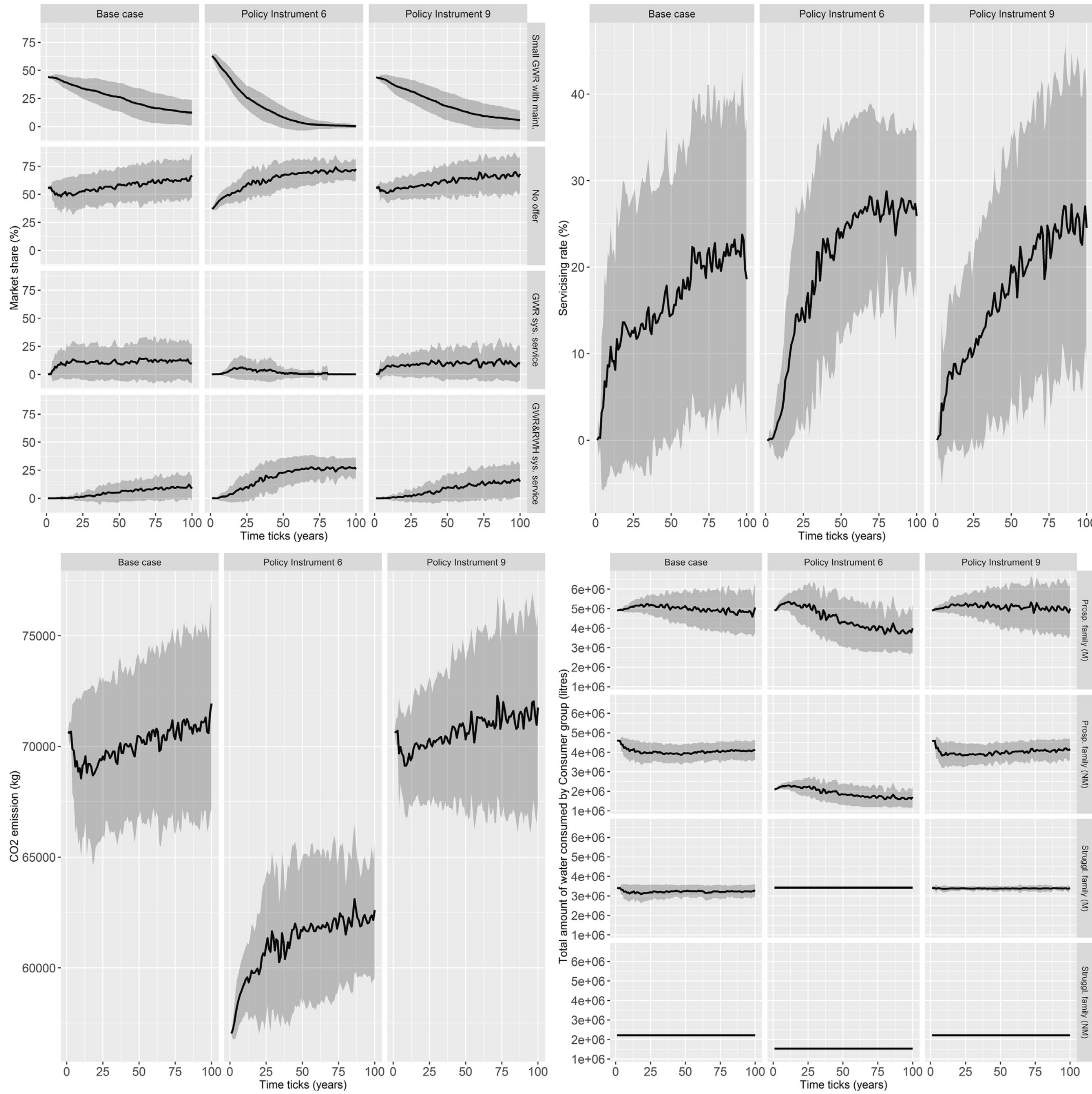

Fig. 4. Example simulation results from the water case: Product/Service market shares (top left), servicising rate (top right), total CO_2 emission (bottom left), and total water consumption for metered (M) and non-metered (NM) Consumer groups (bottom right). The lines represent the average value of the runs, and the borders of the bands indicate the standard deviation.

5. Discussion

5.1. Practical value

The presented servicising model forms a first comprehensive agent-based model for studying possible development paths towards a service economy. It includes interactive decision making processes of both sellers and buyers, in which selling agents apply a price-setting mechanism based on market research, and both selling and buying agents use an additive utility approach with threshold filtering. As a result, the simulated market outcomes emerge from individual choices and interactions. The flexible parametrisation of agents enables the modeller to represent heterogeneous business and consumer types. Furthermore, the model includes various economic, environmental and social output variables, enables the specification of policy instruments and packages, and is *generic*, i.e. can be applied to various economic sectors simply by a different specification of input parameters. Therefore, the model can be used to explore the potential of servicising and servicising policy to contribute to absolute decoupling in various sectors. These abilities have been demonstrated by the servicising case studies illustrated in Section 4.

The practical value of the servicising model for policy makers has been recognised by the European Commission, which in its final project review praised the developed methodology to explore the potential role of servicising and of policy packaging for facilitating a transition to a servicing economy, of which the ABM forms a central part.[13] The simulation results can form a valuable input for the overall policy design and analysis process (Taeihagh et al., 2013). The model and the input data spreadsheet have been carefully designed to facilitate the modelling process (see Section 3.6), but policy makers may need some guidance in understanding which input data is required, specifying the policy-related objects (of which the attributes are more technical), using the right data formats, and setting up and performing experiments and data analysis.

Researchers may use the model to study the overall potential of servicising to realise absolute decoupling. Also, they may use the model to support and improve life-cycle assessment (LCA). Querini and Benetto (2015) have observed that 'ABM seems to be a very appropriate modelling approach for consequential LCAs of large scale policies', as product penetration levels become the result of agent decision making instead of arbitrarily defining them. Our work confirms this suitability. Moreover, it shows that combining ABM and LCA also establishes an integrated assessment of LCA impacts, supply chain GDP, and absolute decoupling.

For businesses, the model may create additional insights on the effects of competition, regulation and market developments on profitability and market share.

5.2. Limitations

The main limitations of the servicising model relate to the model assumptions presented in Section 3.2. The experts within the project accepted these assumptions as simplifications that do not infringe on the model's ability to simulate servicising. For example, the single functional need has been assumed, because multiple needs would come down to multiple markets, while interaction between markets was not considered a main mechanism in servicising shifts. This assumption entailed that rebound effects were not included, however, which may cause an overestimation of environmental benefits.

In addition, some case-specific assumptions may arise from the definition and specification of the case study. For example, in the car and bike sharing case illustrated in Section 4 it has been assumed that the use of cars for car sharing does not impact on the total number of kilometres they can be used. Moreover, the model structure may require a simplified case study representation, e.g. the model's focus on a single need required that in the crop protection case a single pesticide Product represented a combination of pesticide types used for crop protection throughout the season. The model assumptions call for a cautious interpretation of the model results, taking into account uncertainties and expectations about the influence of the market elements abstracted upon.

Furthermore, not all required case study data will be readily available, and many data will be uncertain, which means the modellers and involved case study experts need to make assumptions on input data values. An important example is the required estimation of direct effects of Policy Instruments on behavioural aspects of agents. Furthermore, the conversion to a particular data format will require some estimations, e.g. the Product/Service preference scores must be between 0 and 10.

The influence of data assumptions can be studied through sensitivity analysis in which the influence of the relevant input data on simulation outcomes is assessed. If input data are both uncertain and influential, this should be incorporated in the main findings. A sensitivity analysis of individual input parameters for the project case studies showed that single data input value changes may have a very large impact on the simulation outcomes, but also that the overall sensitivity to input changes can vary widely between cases (van der Veen and Nikolic, 2015).

6. Conclusion and future work

This paper presents a generic agent-based model that can be used to explore the impact of servicising policy on absolute decoupling in various product-based markets. It incorporates business decision making on product- and service-based business models and consumer choices between products and services, includes economic, environmental and social output parameters, and enables the exploration of policy instruments and packages.

The ability of the servicising model to represent servicising shifts has been shown by outlining the model structure, inputs and outputs, and modelling process, and by describing the main mechanisms of the model using a narrative approach. In addition, the ability of the model to analyse the impact of servicising policy on absolute decoupling has been demonstrated by means of three case studies from different sectors.

The research question, 'How can the potential impact of servicising policy on absolute decoupling be explored by means of agent-based modelling, and how can policy makers and researchers be supported in the modelling process?', has been addressed in this paper through the description, demonstration and discussion of the servicising model. The formulation and specification of case studies is facilitated by the use of a single Excel input datasheet with which a case study can be defined and transformed to simulation input, taking away a large part of the complexity of the modelling process. Policy makers may use the model for specific servicising cases to inform the process of policy design and analysis, while researchers may apply the model to further explore the overall potential of servicising and servicising policy to realise absolute decoupling.

The project case study analyses have shown that servicising may lead to absolute decoupling, and that some policy instruments were more effective in stimulating servicising and realising absolute decoupling than others. Policy packages, i.e. combinations of policy instruments, were generally more effective than individual instruments. Detailed analysis results depend on the specific case conditions, stemming from the formalisation of model elements and specification of input parameters, among others the costs, associated materials and preference scores of different products and services, and the decision logic of businesses and consumers.

In future work, the servicising model may be applied to more case studies, to further evaluate the potential of servicising to contribute to absolute decoupling. Furthermore, the scope of the servicising model could be extended and model assumptions could be relaxed. The inclusion of extended supply chains (including upstream suppliers), social networks, and rebound effects may be particularly worthwhile.

Acknowledgement

We thank our fellow project researchers for their contributions to the work presented: Nihan Akyelken, Karen Anderton, and David Banister from Oxford University (mobility case study), Ángeles Pereira, Juan Alberto Turnes Abelenda, Adolfo Carballo, Manuel González, Ana Guerra Fidalgo, Yago Lorenzo Toja, Pedro Villanueva-Rey and Xavier Vence from University of Santiago de Compostela (agri-food case study), Alma López-Avilés, Jonathan Chenoweth,

[13] http://www.tbm.tudelft.nl/en/current/latest-news/article/detail/excellent-ec-review-for-spree/, accessed on 19 July 2016.

Angela Druckman and Stephen Morse from Surrey University (water case study), Vered Blass, Moshe Givoni, Tzruya Calvão Chebach, Anat Tchetchik, Aviad Oren, Noa Meron, Bar Bergman, Elah Matt and Renato Orsato from Tel Aviv University, Eugenijus Butkus, Reda Cimmperman, Eugenijus Stumbrys, Zita Duchovskiene and Agnė Prakapienė from the Research Council of Lithuania, Andrius Plepys, Oksana Mont and Thomas Lindhqvist from Lund University, Jáchym Judl, Sirkka Koskela and Marja Salo from the Finnish Environment Institute, Gerard Dijkema from Delft University of Technology, Dan Kaufmann and Lior Hayoon Davidov from Ben-Gurion University of the Negev, and Yael Marom, Eran Feitelson, Simon van Dam, Inbar Gordon and Tami Schlossberg from the Jerusalem Institute for Israel Studies.

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement FP7-ENV-2012-one-stage-308376 Servicizing Policy For Resource Efficient Economy (SPREE). This document has been produced with the financial assistance of the European Union. The contents of this document are the sole responsibility of the SPREE Consortium and can under no circumstances be regarded as reflecting the position of the European Union.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.01.016.

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