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Heat-as-a-Service (HaaS): a Complex Adaptive Systems perspective on servitization

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ABSTRACT

Servitization increases uncertainty and complexity in manufacturing firms by introducing dynamic interdependencies within and between organisations. This study proposes the conceptual lens of Complex Adaptive Systems (CAS) to frame manufacturers' service delivery systems and a hybrid simulation approach to explore the dynamic interdependencies of their servitization journeys. The case of a boiler manufacturer transforming to a provider of Heat-as-a-Service (HaaS) is used to examine the dynamic interdependencies between the growth of a service business, digitalisation efforts and operational efficiency as well as the interaction between the emerging service- and existing product business. The findings indicate that the manufacturer will experience an initial 'cost-shock' which will significantly decline as service delivery optimises and diagnostic accuracy improves. The study contributes to the servitization literature by introducing CAS as a theoretical perspective and hybrid modelling as a practical approach to explore and reconcile the strategic and operational dimensions of servitization.

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Heat-as-a-Service (HaaS); Complex Adaptive Systems (CAS;); servitization; hybrid simulation

1. Introduction

Manufacturers are increasingly interested in servitization (UKGOV 2018) – a transformation process that manufacturers 'undergo to compete through services rather than through products alone' (Baines, Ziaee Bigdeli, et al. 2020, 1). Servitization is not only expected to add to the manufacturers' competitiveness (Bustinza et al. 2015) but also their resilience (Rapaccini et al. 2020) and environmental sustainability (Doni, Corvino, and Bianchi Martini 2019; Ferreira Junior, Scur, and Nunes 2022). While the benefits of servitization are increasingly recognised, awareness is also growing of the wide range of strategic and operational initiatives the transformation requires and the specific challenges these create (Paton et al. 2021). Servitizing manufacturers are not just required to develop compelling service value propositions (Sjödin et al. 2020) but also need to design service delivery systems to provide their customers with these services effectively (Raja et al. 2018; Sklyar et al. 2019). Servitization requires manufacturers to develop long-term trusting customer relationships (H. Li et al. 2021) while also coordinating the interests and actions of their external delivery partners to maintain these relationships (Gebauer, Paiola, and Saccani 2013). Anticipating and coordinating the range of operational and strategic initiatives that need to form part of the transformation and understanding their potential interdependencies are core challenges for servitizing manufacturers (Pana and Kreye 2021; Khan et al. 2022).

While the coordination of multiple initiatives makes servitization a *complicated* process, it is the dynamic interdependencies of these initiatives that makes it *complex* and creates the substantial management and research challenges (Batista et al. 2017). The complexity of servitization means that manufacturers need to make decisions in non-linear, changing, heterogeneous and emerging contexts (Nilsson and Darley 2006); for example, the quality of the service value propositions manufacturers can offer depends on their collection of customer usage data (Schroeder, Naik, et al. 2020; Zambetti et al. 2021), but access to this data requires high-quality value propositions to attract enough customers in the first place (Rabetino, Kohtamaki, and Gebauer 2017). It is this complexity that makes it difficult for servitization research to develop theory and guidance that heeds the underlying cause-and-effect mechanisms and accommodates the short-term operational and long-term strategic objectives as well as their emerging interdependencies.

On the one hand, servitization research has made good progress in developing generalisable typologies and process maps that help decision-makers develop, monitor and communicate their organisations' servitization initiatives (Sousa and da Silveira 2019; Dmitrijeva et al. 2020). On the other hand, such generalised approaches risk oversimplifying the complexity of servitization and may lead decision-makers to overlook the interdependencies of these initiatives. This, in turn, limits their ability to make correct operational and strategic choices (Waters, Baughman, and Dorsey 2016). Manufacturers start their servitization journeys from different

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positions and develop them in unique ways. Paradoxically, a reliance on generalised approaches may even explain why some of the challenges of servitization, although repeatedly investigated over the years, continue to persist in practice. These include the persistent challenges of determining how and when the financial benefits of servitization will be realised (Gebauer, Fleisch, and Friedli 2005; H. Li et al. 2021), when to integrate external actors in the service delivery (Garcia-Martin, Schroeder, and Ziaee Bigdeli 2019; Khan et al. 2022) and to embed the necessary service learning within the organisation (Kohtamaki, Einola, and Rabetino 2020; Pana and Kreye 2021; Ferreira Junior, Scur, and Nunes 2022). In order to develop servitization theory and provide guidance that helps manufacturers avoid unintended consequences or unsustainable solutions, a research approach is required that considers the interdependencies of the short-term operational and long-term strategic initiatives and embraces the complexity of servitization (Waters, Baughman, and Dorsey 2016).

To help establish such a research approach, this study focuses on the question: *How can decision-makers understand and plan for the systemic changes affecting operations, when pursuing a servitization strategy?* The study adopts a Complex Adaptive Systems (CAS) perspective to conceptualise the decision-making context of servitizing manufacturers (Holweg and Pil 2008; Jones and Corner 2012; Tukamuhabwa et al. 2015). A CAS perspective shifts the research focus from individual cause-and-effect relationships to the structures and feedback loops that create the non-linear interdependencies, individual adaptations and idiosyncratic servitization pathways we can observe among manufacturers (Ziaee Bigdeli et al. 2018). It also enables decision-makers to better understand the interplay between the operational and strategic levels and time horizons that characterise servitization (Jones and Corner 2012). As the case study or survey methods typically used in servitization research (Rabetino et al. 2018) fail to capture these interdependencies effectively, the study uses a hybrid simulation model – integrating the strengths of system dynamics, agent-based and discrete-event simulation methods – to understand servitization dynamics and support management decision-making.

In order to demonstrate and validate the benefits of hybrid modelling to investigate a CAS perspective on servitization, the study examines the case of a heating device manufacturer (HeatCo) considering Heat-as-a-Service (HaaS). The proposal is to move from the transactional sale of boilers to offering integrated solutions that deliver heat and comfort to domestic households. The hybrid simulation is used to explore the complex and dynamic interactions between service growth, operational cost drivers and aspects of organisational learning. It provides the basis for specific recommendations for the case at hand and also offers an important template for modelling the interconnected, complex and dynamic nature of servitization in future research.

Hence, the study contributes to servitization theory by (i) introducing the theoretical CAS concept and showing how it sheds light on the service delivery network and its underlying dynamics, (ii) proposing hybrid simulation as a method to integrate critical learning and servitization considerations, and (iii) shedding light on the nested processes that contribute to the service paradox.

The following section specifies the servitization challenges and their complexity implications and outlines the opportunities a CAS perspective and hybrid simulations provide. Next, the methods and case study are explained before the simulation findings are presented. Finally, the practical and theoretical implications as well as suggestions for future research are discussed.

2. Background

2.1. Servitization and its challenges

Servitization, the transformation manufacturers go through as they shift from competing through products to competing through services, requires a wide range of strategic and operational changes. These include changes to the manufacturers' product design ('design for service'; Solem et al. 2021, Beltagui 2018), sales approach ('consultative sales'; Salonen and Terho 2021), their finance arrangements ('finance for services'; Baines, Ziaee Bigdeli, et al. 2020) and business network configuration ('partner model'; Garcia-Martin, Schroeder, and Ziaee Bigdeli 2019). Importantly, these strategic and operational elements are not only directly affected by servitization but also indirectly affect each other, adding to the complexity of the transformation (Parry and Tasker 2014; Struyf et al. 2021). Arguably, several of the persistent challenges servitization research focuses on (i.e. the service paradox, the orchestration of the value network and the management of organisational learning) are exacerbated by the underlying complexity of servitization.

The service paradox (Gebauer, Fleisch, and Friedli 2005) describes the widely observed challenge of manufacturers' service investment and growth, resulting in increased service costs without generating the expected returns. The literature largely approaches the paradox from a strategic perspective, suggesting that the financial benefits of servitization take time to accrue (Kastalli and Van Looy 2013) and are affected by scale-dependent service efficiencies (Fang, Palmatier, and Steenkamp 2008). However, little insight is offered as to how much time or what scale is required for the financial benefits to accrue; yet, continuing with unprofitable services may lead to servitization failure (Valtakoski 2017) and threaten the viability of the wider business (Neely 2008). Without considering which operational developments would create these service efficiency gains over time and how these would dynamically interact with manufacturers' growth strategy, no precise answers on the service paradox can be given.

Several authors explicitly focus on the complexity of servitization to better understand the root causes of the service paradox. Tazaïrt and Prim-Allaz (2021), in particular, highlight the interdependency between servitization and digitalisation in order to create the desired efficiencies and values. Yet, manufacturers struggle to coordinate their different objectives and interdependencies. To deal effectively with servitization complexity, Brax et al. (2021) and Sjödin, Parida, and Kohtamäki (2019) advocate a configurational research approach. Such an approach recognises that manufacturers follow different transformation pathways which may or may not be effective in distinct organisational contexts. To accommodate the non-linear and dynamic nature of the servitization-performance relationship, Sjödin, Parida, and Kohtamäki (2019) also call for longitudinal perspectives on servitization to identify the trade-offs and individual trajectories that manufacturers follow.

The manufacturers' external value network plays an important role in service development (Garcia-Martin, Schroeder, and Ziaee Bigdeli 2019) and delivery (Rabetino, Kohtamaki, and Gebauer 2017), and the effective orchestration of this network has been identified as another critical servitization challenge (Baines et al. 2017; H. Li et al. 2021). Other studies identify network orchestration as a core servitization capability (Raddats et al. 2017), which should be explicitly recognised in the development of a servitization roadmap (Reim, Sjödin, and Parida 2019). Importantly, Zhou et al. (2021) emphasise the need to investigate how the network orchestration requirements differ between the early and late servitization stages as these will determine the manufacturers' service innovation and service efficiency (and resulting financial performance). Zhou et al. (2021) also demonstrate that the integration of network partners may improve the profitability of basic services but create tensions when pursuing more advanced service offerings.

Although extensive integration with external actors helps servitizing manufacturers to deliver their core value proposition, it also creates additional complexities that need to be recognised and managed (Gebauer, Paiola, and Saccani 2013; Gölgeci et al. 2021). As the capabilities of each actor are important for servitization success, researchers (Johnson et al. 2021; Marcon et al. 2022) advocate the use of multi-actor perspectives to capture the complexity of servitization effectively. In addition, Eloranta, Ardolino, and Saccani (2021) encourage servitizing manufacturers to adopt complexity management techniques to better identify, quantify and navigate their value network. While existing research highlights the complexity that servitization creates across the value network, the corresponding studies are largely of theoretical (Eloranta, Ardolino, and Saccani 2021; Gölgeci et al. 2021) or qualitative nature (Gebauer, Paiola, and Saccani 2013; Marcon et al. 2022) and do not always communicate the magnitude of the changes faced by manufacturers and their networks.

With servitization representing a significant change effort for manufacturers, studies also highlight organisational learning as a persistent challenge. While early servitization studies emphasise the challenge of embedding service learning into the servitization process (Gustafsson, Edvardsson, and Brax 2005; Macdonald et al. 2011), more recent studies specify these learning needs: Kohtamaki, Einola, and Rabetino (2020), for instance, explain how manufacturers need to simultaneously engage in explorative and exploitative learning (i.e. learning to develop new services versus learning to incrementally improve service practices) as part of their servitization efforts. Schroeder, Naik, et al. (2020) outline how both of these learning objectives are achieved by digitalisation. Zambetti et al. (2021) also create a framework for demonstrating how digital data, combined with analytics and automation, offers learning and improvement opportunities along with increased customer value.

However, researchers also highlight how digitalisation not only supports the servitization-related learning needs but also adds to the complexity of servitization (Struyf et al. 2021; Chen et al. 2022). As the digital solutions that support servitization become more advanced, the intrafirm and interfirm interdependencies with the service network increase (Sklyar et al. 2019). Learning how to manage the complexity of digital inter-connectivity becomes a critical servitization capability in itself (Struyf et al. 2021). Valtakoski (2017) goes beyond the servitization complexity challenges that originate from digitalisation to conceptualise servitization as a complex change that requires manufacturers to gain tacit knowledge to achieve the effective integration of a variety of interdependent components.

2.2. Conceptualising servitization as a CAS perspective

As shown above, prior research has not only identified several core challenges of servitization but has also identified the complexity of servitization as a critical factor that contributes to these challenges (e.g. Brax et al. 2021), with several authors calling for investigations of this complexity to help address the challenges (Eloranta, Ardolino, and Saccani 2021; Struyf et al. 2021). In response to such calls, the present study draws on the concept of CAS as the theoretical lens to formalise our understanding of the complexity in servitization and provide avenues for its effective management.

A CAS describes a system where non-linear high-level behaviours are influenced by lower-level dynamics (Rammel, Stagl, and Wilfing 2007). Many systems are complex (e.g. machines comprised of many components) but not adaptive (i.e. the behaviour of the components and the machine remain predictable). A CAS can be defined as a *hierarchically* structured grouping of *heterogeneous* components, jointly exhibiting *emergent* behaviour (Choi, Dooley, and Rungtusanatham 2001; Oughton et al. 2018). The hierarchical CAS arrangements highlight the nested processes that characterise the system and their overall dynamics (McCarthy et al. 2006). In the servitization context these can be seen both internally and externally; the direction and success of servitization are reliant on the internal interactions between manufacturers' strategic, tactical and operational components (Lenka et al. 2018), as well as their external network interactions (Story et al. 2017; Garcia-Martin, Schroeder, and Ziaee Bigdeli 2019; Baik, Kim, and Patel 2019). The heterogeneity of the components, which may or may not have agency and behave differently (Levin 1998; Allen and Starr 2017), further adds to the complexity of a CAS as it makes the system's behaviour unpredictable. In a servitization context this heterogeneity relates to the diversity of internal and external actors, such as customers whose idiosyncratic product utilisation makes service delivery continually challenging and servitization complex (Batista et al. 2017; Schroeder, Naik, et al. 2020; Naik et al. 2020). Raja et al. (2018) find three different approaches to servitization, supported by different organisation designs within a single company. Emergence refers to the continuous dynamic interaction of components and their subsequent evolution (Johnson 2018; Tolk 2019) which characterises a CAS (Holland 1992; Choi, Dooley, and Rungtusanatham 2001). Emergence in a servitization context is highlighted in longitudinal studies that reveal evolving pathways and demands (Kowalkowski et al. 2012; Martinez et al. 2017; Dmitrijeva et al. 2020) and the role of 'punctuated equilibrium', the shift between small, incremental and discontinuous radical changes in servitization (Baines, Ziaee Bigdeli, et al. 2020).

Applying the CAS perspective to examine servitization provides an opportunity to highlight some of its core attributes, understand its underlying dynamics (Dmitrijeva et al. 2020) and to see how it can be controlled (Nair and Reed-Tsochas 2019). A CAS perspective has been noted for its particular theory development opportunities (Davis, Eisenhardt, and Bingham 2007), in particular by: (i) providing insights into complex theoretical relationships, especially when empirical data limitations exist; (ii) helping to specify the assumptions and theoretical logic that are at the heart of underlying theories; (iii) showing the outcomes of interactions of multiple underlying organisational and strategic processes as they unfold over time. The servitization challenges outlined above include interdependencies between components and actors that are dynamically reconfiguring over time and lead to unpredictable or paradoxical performance effects. This study proposes that a CAS perspective helps to uncover the nature of relationships and change to make sense of the paradoxes.

2.3. Investigating a CAS perspective on servitization

Investigations that study specific CAS attributes regularly employ simulation methods, individually or in combination (e.g. G. Li et al. 2009; Burns et al. 2017). To develop a holistic approach to study servitization, the present study will integrate system dynamics (SD), agent-based (AB) and discrete-event (DE) simulation methods. Each method provides particular strengths (and limitations) and has individually been used in previous servitization studies to examine specific aspects of the manufacturers' servitization journey.

SD has been used in several servitization studies to understand the long-term implications of specific service configurations. The method offers a macro-perspective of a system (Sterman 2000; Mykoniatis and Angelopoulou 2020) and provides an opportunity to experiment with parameters to understand a system's emergent behaviour (Morecroft and Robinson 2005; Borshchev et al. 2014). SD has been used to examine how servitizing manufacturers are impacted by different service levels (Legnani et al. 2010; Ritola and Coatanéa 2013; Schmidt-Costa, Uriona-Maldonado, and Possamai 2019), how the long-term growth in servitization capabilities affect corporate performance (Rodrigues, Pigosso, and McAloone 2017) and how it develops over its lifetime (Lee, Han, and Park 2015). However, while SD is very useful in investigating the long-term dynamics of servitization, the method, on its own, cannot represent the *heterogeneity* (e.g. individual customer demand) and the *hierarchical* nature (e.g. the interdependence between micro- and macro-developments) that contribute to the complexity of servitization (Batista et al. 2017; Schroeder, Beltagui, et al. 2020; Naik et al. 2020).

In contrast to the high-level SD approach, AB simulation provides a micro-level, short-term focus that considers individual, heterogenous and self-directed components (agents) (Nilsson and Darley 2006) and determines the set of rules and properties that direct agents' decisions and their emergence over time (Borshchev et al. 2014; Hajmohammad and Shevchenko 2020). AB simulations have been used in a servitization context to investigate how individual technicians' qualifications or maintenance schedules affect service performance (Lagemann and Meier 2014) or how individual customers' preferences affect services (van der Veen, Kisjes, and Nikolic 2017). These studies model customers (Wrasse, Hayka, and Stark 2015; van der Veen, Kisjes, and Nikolic 2017), manufacturers (Rondini et al. 2017), service providers (Maisenbacher et al. 2014; Wrasse, Hayka, and Stark 2015), technicians (Lagemann and Meier 2014; Wrasse, Hayka, and Stark 2015) or even products (Wrasse, Hayka, and Stark 2015; Lieder et al. 2017) as agents that exhibit individual behaviours[1] which shape the system performance.

DE simulations experiment with core parameters of distinct processes that may affect performance outcomes (e.g. Shi et al. 2015). DE simulations in the servitization context are largely used to shed light on operational-level challenges; for example, investigating how process waiting times affect service satisfaction (Pezzotta et al. 2016), how varying maintenance schedules affect product-service failures (Silva Teixeira, Tjahjono, and Alfaro 2012) or how service-delivery processes compare in alternative servitization contexts (Kuo 2011; Alix and Zacharewicz 2012; Chalal, Boucher, and Marques 2015; Alabdulkarim, Ball, and Tiwari 2015). These studies experiment with resource capacity (e.g. sales or technical staff availability), event triggers (e.g. service demand or utilisation) or the nature of services offered. However, DE simulations on their own do not capture the heterogeneity of the entities investigated and do not represent the emergent nature of particular phenomena.

A small number of servitization studies have started to integrate these simulation methods in order to complement their strengths to investigate specific aspects of the manufacturers' servitization journey. Of particular interest are the interaction points defining how the simulation methods are linked (i.e. the output of one simulation feeds into other simulations) (Zhu and Chertow 2017). Rondini et al. (2017) integrate DE and AB simulations to show how maintenance processes (through DE) are affected by heterogeneous customer preferences (through AB) with the customers' decision as the interaction point linking both simulations. Lieder et al. (2017) also integrate DE and AB simulations to show how remanufacturing and recycling processes (DE) are affected by product and component lifetime heterogeneity (through AB) using the component's lifetime as the interaction point. Integration of SD with AB simulations is provided by Asif, Lieder, and Rashid (2016), who show how long-term progress in production and inventory levels (through SD) interacts with the consumers' buy/lease decisions (through AB) which also forms the interaction point.

However, the integration of all three simulation approaches in a servitization context has been limited. Although Wang, Breme, and Moon's (2014) simulation of long-term material flows, energy usage and feedback loops cover production processes (DE), consumer behaviour (AB) and material flows (SD), these simulations are only operating in parallel with no direct interaction.

This section highlights how different simulation approaches are used in servitization research and how individual studies are starting to integrate them to understand the dynamics of specific aspects of servitization. To contribute to the development of a holistic CAS perspective that captures the strategic and operational dynamics of servitization, the present study uses a concrete case to illustrate how a hybrid simulation integrating SD, AB and DE simulations can represent the *hierarchical*, *heterogenous* and *emergent* attributes of servitization and support the decision-making of servitizing manufacturers.

3. Methods

3.1. Research setting

To explore how hybrid simulations can support the understanding of servitization and help managers with their decision-making, we draw on field research, conducted with a manufacturer of domestic boilers (HeatCo), exploring the service delivery implications of a Heat-as-a-Service (HaaS) offering. Hence, the HaaS delivery network represents the focal system of the study.

The use of a domestic customer-focussed case offers an opportunity to investigate service delivery implications at a higher scale than industrial-focussed servitization cases would normally provide. The hybrid simulation was developed iteratively through a series of five workshops over approximately nine months and validated through presentations and interviews with key decision-makers. The key parameters of the simulation were provided by HeatCo in the workshops, with reference to industry standards.

HeatCo is still in the early stage of servitization (Baines, Bigdeli, et al. 2020), as it seeks to identify the opportunities that servitization offers but also the possible implications it creates. It seeks to change its product-focussed business model by offering households an outcome-based HaaS value proposition including predictable costs and fuel efficiency. In its current product-focussed model, boilers are sold through independent contractors who also provide installation and maintenance services. In a future HaaS model, HeatCo will not only provide the boilers as part of its service value proposition but will also be responsible for the ongoing maintenance and repair requirements. The proposed changes will mean the system evolves from a manufacturing- and distribution-oriented supply chain to a more complex and collaborative service-oriented value network.

HeatCo has recently begun integrating digital sensors into its products, gathering product usage data and analysing this data to gain insights into operational challenges and process efficiency. Questions are being raised about the short- and long-term service delivery costs and resource requirements that a HaaS offering would create and how the HaaS delivery would interact with the service commitments that remain from the current product-focussed business model (i.e. warranty). The application of the CAS perspective helps in understanding the core characteristics of the HaaS delivery system (i.e. hierarchy, heterogeneity and emergence) and provides the basis for the subsequent development of the hybrid model.

The *hierarchical* nature of the HaaS delivery system is reflected by the interactions of multiple components (e.g. customers, technicians, boilers), creating interdependent, operational and strategic challenges. One operational challenge is the 'second visit problem' which occurs when a technician visits a customer to perform a repair but is unable to complete the work (due to missing spare parts or tools), so a second visit is required. In a HaaS context, as HeatCo is responsible for maintenance and repair, second visits reduce its service efficiency contributing to the service paradox. The operational service delivery challenges are affected by long-term strategic challenges related to designing a system which creates the required efficiency and enables an efficient service to be delivered at scale. The strategic challenge for HeatCo is to understand what efficiency gains can be achieved, how the existing service commitments (i.e. warranty) will unfold, how fast the service delivery network needs to grow and, ultimately, how fast the HaaS offering can be grown so it can still be delivered.

The *heterogeneity* of the HaaS delivery system's core components emerges as one of its core characteristics: customers vary in usage patterns; technicians vary in skill levels and locations; boilers vary in specifications and age but may also be part of either a HaaS contract or a conventional product sale and may still have warranty cover.

The *emerging* nature of its HaaS delivery system can be expected to support HeatCo's ability to efficiently deliver services at scale. The service efficiency challenge (i.e. the second visit problem) captures the difficulty of accurately diagnosing repair needs and enabling continuous learning to improve diagnostic accuracy sufficiently. Although sensors and digital connectivity help with diagnostics, continuous observations from the device are required to enable continuous learning, improve diagnostic accuracy and minimise second visits. Improved diagnostic accuracy also enables remote-fix options, where device resetting, or recalibrating, removes the need even for a first visit, so further improving service efficiency.

Its *hierarchical*, *heterogeneous* and *emergent* nature makes the understanding and planning of HaaS delivery very difficult. Decision-makers require an integrated representation of the diverse and interdependent actors and an understanding of how the HaaS delivery system's state is likely to evolve over time to inform their servitization strategy and align their resources.

3.2. The hybrid model

To build a representation of HeatCo's HaaS delivery system that supports strategic (i.e. the HaaS adoption target) and operational decisions (i.e. resource allocation, capacity management and process design), we created a hybrid model that represents core aspects of its CAS nature. As summarised in the form of a causal loop diagram in Figure 1, the hybrid model integrates critical product, customer and service elements that interact in a HaaS service delivery system, recognises their variability (i.e. warranty levels) and captures the improvement of its diagnostic accuracy. For HeatCo, to avoid being overwhelmed by the costs of service delivery (i.e. the service paradox), understanding how these costs are affected by the number of service requests and their cycle time is critical. Figure 1 illustrates how HeatCo's number of service requests is not only affected by the amount of HaaS customers but also the amount of conventional customers in combination with the remaining warranty periods of their boilers. In addition, it illustrates the non-linear properties of the service cycle time: although service delivery creates costs, it also leads to opportunities to improve learning and diagnostic accuracy and, therefore, the cycle time of future service requests (i.e. reducing second visits), which will affect service delivery costs in turn. Figure 1 also takes into account that the service cycle time will be affected by digitalisation (as it improves repair instructions and remote-fix opportunities). The applications of the SD, DE and AB methods that operationalise the hybrid model are specified next.

3.2.1. System dynamics model

The SD part of the hybrid model (Figure 2) represents the long-term strategic level of the HaaS delivery system and its evolution over time. It shows the adoption of HaaS (from *conventional_customers* to *HaaS_customers*) and captures the learning effect (diagnostic accuracy) that boiler repairs create. The variable *accurate_repair_data_stock* represents the amount of repair data collected in relation to every warranty or HaaS-based service request which increments the diagnostic accuracy using a decreasing rate of change (following Morrison 2008; Gunawan 2009). The SD model has interaction points with the DE and AB models (capturing the operational processes), as indicated by the dashed arrows (in Figure 2). The SD model's *accurate_repair_data_stock* is informed by the fixes of boiler faults created in the repair process (captured by the DE model). The *diagnostic_accuracy*, in turn, informs the probability of a correct remote diagnosis for individual boilers (captured by the AB model).

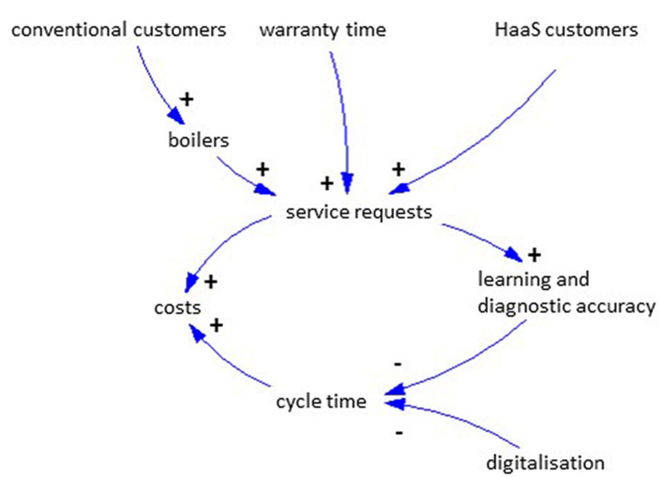

Figure 1. Causal loop diagram presenting the most relevant variables driving servitization dynamics.

3.2.2. Discrete-event model

The DE model zooms in on the repair process (Figure 2), following Rondini et al. (2017). The process commences with the fault detection (*boilerFails*) which triggers a remote diagnosis (based on customer and sensor information), followed by a repair request for a technician (*technicianNeeded*, *seizeTechnician*). In the case of technician capacity constraints, repair requests will queue in the block *seizeTechnician*, creating a waiting time in the variable *serviceDelay* and will be released upon completion. A possibility for *remoteRepair* is included which becomes increasingly likely with further digitalisation. The DE model (capturing the repair process as an aspect of the short-term operational level of the HaaS delivery system) interacts with the SD and AB models through interaction points, as indicated by the dashed arrows (Figure 2). The DE model's *serviceDelay* is informed by the job completion time (input by the AB model). The model's number of *correctly fixed boilers* informs the *accurate_repair_data_stock* in the SD model. We argue that only HaaS or warranty-based repairs are recorded properly as they are conducted by HeatCo's specially trained technicians.

3.2.3. Agent-based model

While the SD model captures the context change over time and the DE model captures the repair process, the AB model zooms in on the heterogeneity of the technician and boiler attributes (following Wrasse, Hayka, and Stark 2015; Rondini et al. 2017) (see Figure 2). Technicians are modelled as agents that have a current state (*idle, travel, repairing*) and a virtual location. Technicians are *idle* until assigned to a repair (*seizeTechnician*, DE model), at which point they travel to the customer at a randomly assigned distance. The technician confirms the accuracy of the initial remote diagnosis (required experience, spare parts and tools leading to repair) or decides that a second visit is required (leading to repair delay).

Boilers are also modelled as agents that have a lifespan (*boilerAge*) and probability to fault (*timeToFailure*), a virtual location and an association to either a conventional or HaaS contract. They are assumed to fail at least once within the first 12 years, at least one more time within six years after that and to be replaced at the end of their 18-year lifespan. The AB model interacts with the SD and DE models through interaction points, as indicated by the dashed arrows. The *rate of correctly diagnosing failures on the agent level* is affected by the organisation's emerging *diagnostic accuracy*

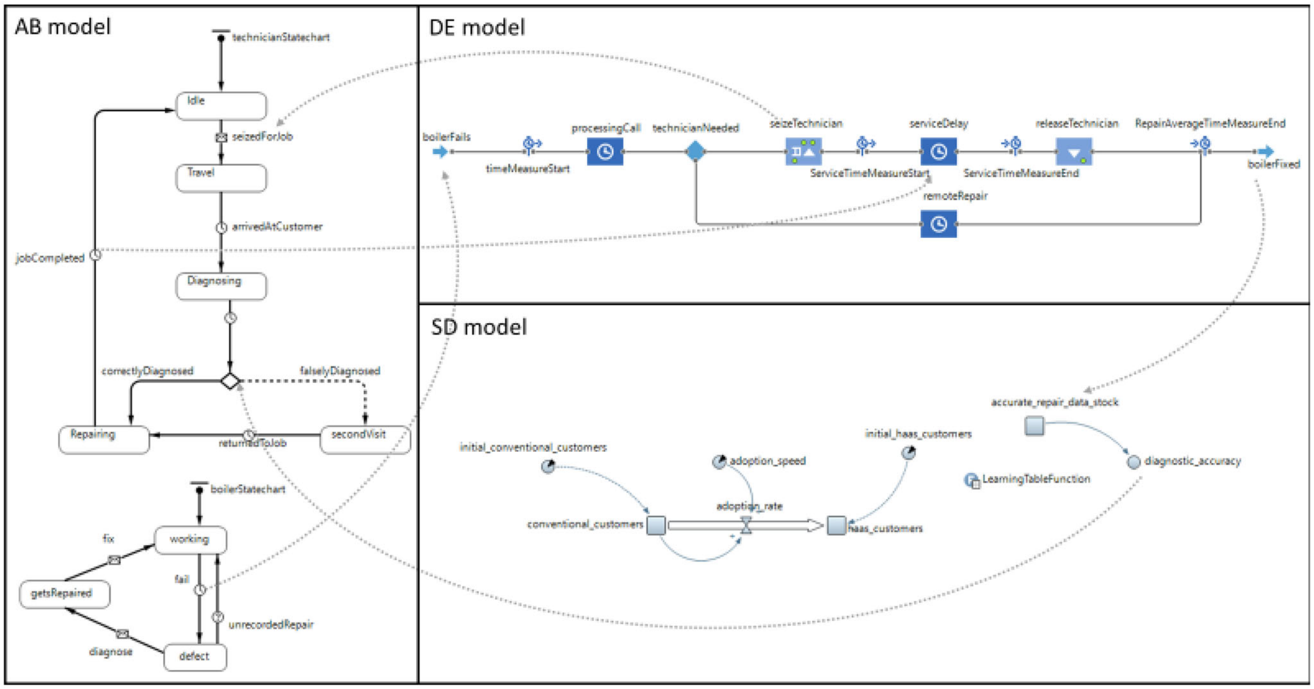

Figure 2. Hybrid model overview (AB: statecharts of technician and boiler agents. DE: repair service process. SD: effect of data-based learning on diagnostic accuracy).

(captured by the SD model). The AB model's *boiler failure* triggers the repair process in the DE model.

3.3. Model validation

The hybrid model was tested using extreme conditions and sensitivity tests (Sterman 2000), which confirmed that the essential variables, determining the dynamics of the real-world system, are integrated. Based on the computational resources available, a simulation of a maximum of 16,000 boiler agents over a time frame of 18 years could be tested. Results showed that lower technicians-per-device ratios lead to longer queuing times for service requests and that the rate of work of the technicians and average cycle time in the model are in line with field data. Additional model reporting is provided.[2]

Further, a validation workshop was conducted with HeatCo representatives to confirm the usefulness of the hybrid model as a tool to support decision-making in a servitization context (following Nilsson and Darley 2006). The feedback specifically confirmed the hybrid model's usefulness for supporting long-term decision-making on service delivery: comments stated that the greatest value of the hybrid model is to provide decision-makers with an understanding of the dynamics of the (future) context and how this context is shaped by the decisions taken in the present. Representatives also emphasised that the explicit consideration of the diagnostic accuracy based on repair data helps in understanding how decisions around data and agents influence the second visit problem. Further, representatives explained that the simulations of varying HaaS market diffusion rates confirm their assumptions about the time it would take to improve service delivery efficiency to a level where HaaS becomes profitable.

4. Findings

4.1. Overview and scenario setting

Three key findings emerged from the simulation and validation of HeatCo's HaaS delivery system. First, the shift from conventional to HaaS customers increases requests for maintenance and repair service. Second, the increase in service requests, associated data collection and learning creates service efficiency. Third, the growth in HaaS adoption creates an initial 'cost-shock' before the increase in service efficiency reduces the service costs. Figure 3 shows the findings of nine simulated scenarios to understand how aspects of HeatCo's service delivery system are affected by a growth in HaaS adoption. The variable *adoption_rate* describes the annual share of conventional customers (0%, 10% or 20%) that are adopting HaaS contracts, thereby determining the growth of HaaS customers. The various growth rates aim to inform decision-makers about their organisation's sensitivity towards varying market diffusion rates of service-based business models. The variable *warranty_period* defines the average warranty period for boilers (5, 7.5 or 10 years) that were sold to conventional customers. The warranty periods are chosen to cover premium as well as minimum levels of warranty. The nine scenarios are each simulated with a population of 10,000 boilers and 50 technicians over a period of 18 years.[3] The cycle times are the average time it takes to address a service request each month (including a second visit if required) for each scenario. The number of service requests is the sum of monthly maintenance and repair service requests for HaaS customers and conventional

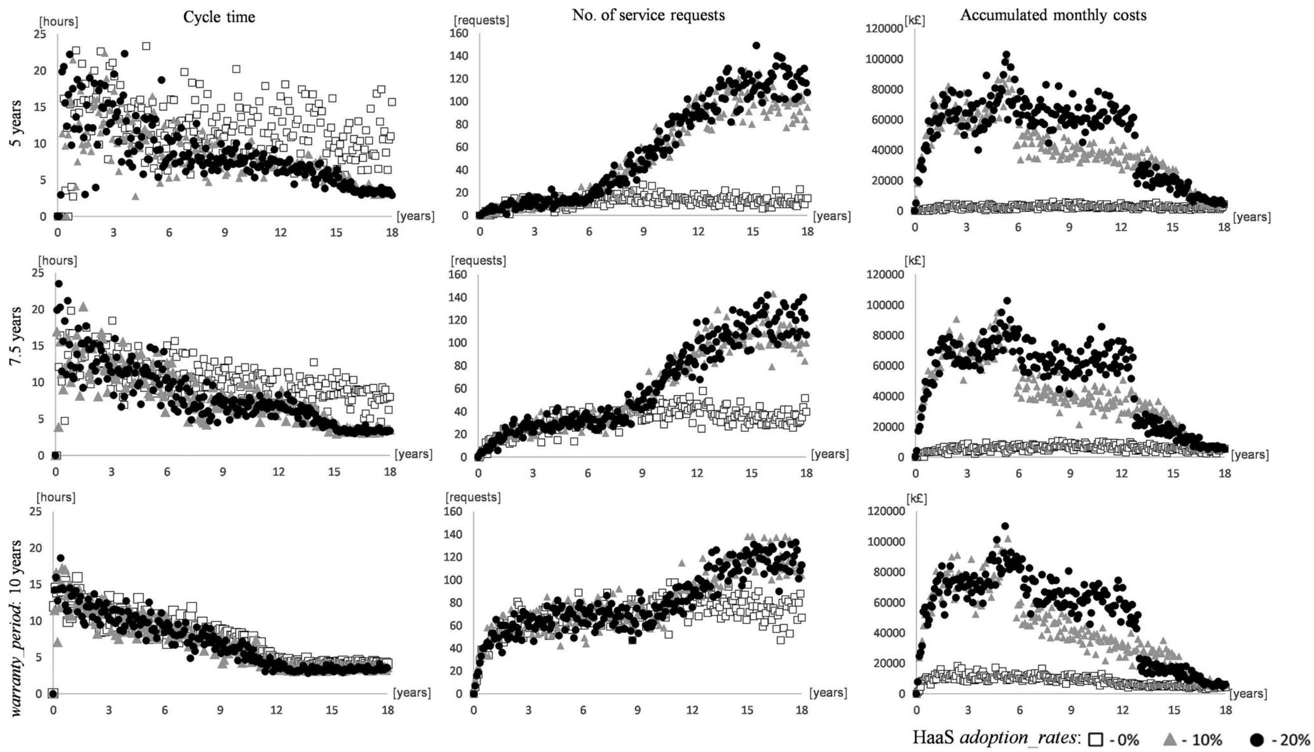

Figure 3. Overview of the hybrid simulation results.

customers within their warranty period. The accumulated monthly costs refer to the costs created by the HaaS customers (services and boiler installation) and conventional customers (warranty-based services).

4.2. Rate of change in HaaS affects number of service requests

The simulation shows how the growing HaaS adoption creates capacity implications for HeatCo's service delivery system. The increase in service requests shows the compounding effect of the increase in maintenance and repair services related to the growing HaaS contracts and the services related to the conventionally sold boilers that are still within the warranty period. Figure 3, middle column, shows the service requests based on different HaaS adoption rates and warranty lengths for conventionally sold boilers. As older boilers require more maintenance and repair, the number of HaaS-based service requests become noticeable as the respective boilers are starting to age.

4.3. Increase in diagnostic accuracy reduces cycle time

The simulation also shows how the growing HaaS adoption contributes to the efficiency of HeatCo's maintenance and repair services. Figure 3, first column, shows how in all scenarios the average service cycle times steadily decrease as learning (i.e. diagnostic accuracy based on increased data availability and connectivity) increases service efficiency (i.e. reduction of second visits). The 0% HaaS adoption scenarios across all three warranty periods show a slower decrease of cycle times as the learning is limited to warranty-based maintenance and repair services.

Interestingly, in the ten-year warranty scenario (0% HaaS adoption), the cycle times develop nearly identically to the 10% and 20% HaaS adoption rates because, due to long-term engagement, usage data comparable to the HaaS contexts is collected. The simulations further show that the cycle time in the 20% HaaS adoption scenario is not reduced faster than in the 10% adoption scenario (despite higher data availability and additional learning opportunities). This is explained by the limited capacity of HeatCo's service delivery system where a rapid growth of service requests causes additional queueing (as a secondary problem) which overshadows the service efficiency gains.

4.4. HaaS leads to higher service delivery costs

The simulation also shows the service delivery costs that the HaaS adoption creates for HeatCo (Figure 3, third column). Generally, the growing HaaS adoption creates an initial 'cost-shock' (due to the costs of the HaaS-based boiler installations and not yet optimised service delivery), which extends over a period before the service delivery costs decline significantly (due to optimised service delivery based on better diagnostic accuracy) (see Appendix A). After 18 years,[4] the monthly service delivery costs for the 20% and 10% HaaS adoption rates are almost the same as for the 0% adoption rate, because the HaaS-based boiler installations are completed and the service delivery is optimised. As the model only considers the cost side and not the revenue side of HaaS contracts, statements on the overall financial performance cannot be made.

5. Discussion

Servitization is a complex transformation process that creates fundamental changes across manufacturers' strategic and operational considerations (Rabetino, Kohtamaki, and Gebauer 2017). This research uses a CAS perspective to uncover and explore the underlying complexity of servitization (Choi, Dooley, and Rungtusanatham 2001; Oughton et al. 2018) and proposes hybrid simulations (combining SD, AB and DE models) to simulate the dynamics and support organisational decision-making. Our findings provide concrete insights for the design of HeatCo's HaaS delivery system as well as wider managerial and research implications.

5.1. Insights from the hybrid simulation

Modelling of the HeatCo case demonstrates how hybrid simulations can help servitizing manufacturers understand and manage the challenges of orchestrating their external network, embedding organisational learning and overcoming the service paradox. This leads to a number of insights related to the system and its evolution.

5.1.1. Network orchestration

First, the findings shed light on the service capacity requirements that servitization creates for HeatCo and its service delivery network by showing how the growing HaaS adoption affects the number of service requests HeatCo will receive. Importantly, the service capacity requirements not only include maintenance and repair services for the customers on HaaS contracts but also for those customers whose conventionally sold boilers are still within the warranty period. The findings show that, for HeatCo to be able to deliver its HaaS offering, the ability to scale up and integrate a network of external contractors is critical. The findings also show how careful considerations of the individual attributes of these contractors support their integration and the management of the service delivery system. The ineffective allocation of service jobs across HeatCo's network (using contractors' individual attributes; AB model) affects its customers' waiting times (i.e. service delay; DE model), damage customer satisfaction and may incur penalties.

Although the literature increasingly recognises the importance that service delivery networks have for manufacturers' servitization journeys (Khanra et al. 2021), a conceptualisation of their underlying dynamics and an understanding of the effective orchestration of network members are still lacking. In particular, the literature explains that servitization requires manufacturers to govern their network in different ways (e.g. Kapoor et al. 2021; Johnson et al. 2021) but without specifying the dynamic mechanisms that affect manufacturers' roles. Our study fills this gap by illustrating how servitization gradually increases the manufacturers' dependence on their network which creates the need for new forms of interaction and coordination. At the same time our study also highlights how the role of the network changes in the course of manufacturers' servitization. Prior studies emphasise the network as a source of critical capabilities that support manufacturers with the *development* of their advanced services (e.g. innovation capabilities or digital capabilities) (Reim, Sjödin, and Parida 2019; Linde et al. 2021). In contrast, our study and findings emphasise the network as a source of critical capacity that supports manufacturers with the *delivery* of their advanced services, a perspective that is still developing (Khanra et al. 2021). While it is important to understand the network as a source of capabilities for the development of advanced services, this needs to be complemented by an understanding of the network as a source of capacity that can provide the scale and therefore viability of the servitization objectives.

5.1.2. Organisational learning

Second, the findings show the importance of explicitly considering 'learning' in the design and management of the service delivery network. The efficiency of HeatCo's maintenance and repair services (DE model) is co-determined by the increase in diagnostic accuracy (SD model) which is accelerated by its growth in HaaS adoption. Understanding how learning is driven by the growth in service customers is critical for decision-makers at HeatCo who need to balance between investments into service capacity (more maintenance staff) and diagnostic accuracy (increased efficiency), which is instrumental in reducing the service capacity required. Although the critical service efficiency will benefit from a larger HaaS customer base (first column of Figure 2), growing the service business too quickly would place an excessive burden on the service capacity (middle column of Figure 2); HeatCo's growth strategy needs to carefully consider these dynamics.

These considerations and findings expand the way learning is approached in the servitization literature, which already emphasises the importance of learning as a critical input for effective service development (Baines, Ziaee Bigdeli, et al. 2020), service implementation (Karatzas, Papadopoulos, and Godsell 2020; Dmitrijeva et al. 2020) and service improvement (Beltagui 2018). We expand these insights by adopting a CAS perspective that recognises learning as an input as well as an output of servitization. This perspective also helps to integrate studies that focus on the digital aspects of servitization with those that cover learning aspects. Studies emphasise how digitalisation helps to manage the risk of servitization or create efficiencies (e.g. Paschou et al. 2020) for service delivery, but often they do not recognise how digitalisation can affect learning and how this contribution could be further developed by specific digital design choices.

5.1.3. Service paradox

Third, the study and its findings also help to better explain the emergence of the service paradox – the failure of service investments to generate the expected returns (Gebauer, Fleisch, and Friedli 2005). The findings indicate that HeatCo will experience an initial 'cost-shock' (due to the costs of HaaS-based boiler installations and not yet optimised service delivery) (third column, Figure 3). However, they also show that this increase is temporary as the service delivery costs will significantly decline over a longer period (due to optimised service delivery based on better diagnostic accuracy) (see Appendix A).

While prior studies already recognise how the service paradox can (at least partly) be explained by the lack of economies of scale and time delay (Neely 2008; Kastalli and Van Looy 2013; Szasz et al. 2017), and identify the non-linear nature of the critical efficiency gains (Kohtamäki et al. 2013; Feng et al. 2021), our study illustrates and models the wider complexity of the service delivery system which provides opportunities to specify interventions that may shorten the service paradox.

5.2. Managerial implications

For many manufacturers servitization creates significant uncertainties (Zhang and Banerji 2017), which may even lead to forms of resistance (Hernandez and Kreye 2021). Especially in the early exploratory stages (Baines, Bigdeli, et al. 2020), where few pilots have been conducted that provide confidence in the opportunity and viability of servitization to the wider organisation, opportunities to communicate the changes and illustrate the implications are critical to create wider buy-in (Dmitrijeva et al. 2020).

The CAS perspective helps decision-makers to create strategic and operational insights on the emergent properties of servitization and assess the interactions between individual functions and their consequences for the whole system (Anderson 1999; Liu, Tong, and Sinfield 2020). The hybrid simulation operationalises the CAS perspective on servitization as (through its nested approach) decision-makers can selectively apply different levels of abstraction (Borshchev 2013) and experiment with different scenarios. These critical managerial implications are confirmed by a senior HeatCo decision-maker who, upon reviewing the simulation, commented:

> The tactical advantage of the modelling is operational efficiency. The benefit […] is informing your choices and being able to play around with different scenarios and think about what choices you are going to make.

In addition, the model development and simulation can serve as an important tool to create a shared understanding of the servitization journey (Warren and Langley 1999; Black 2013; Cosenz and Noto 2016) and communicate the vision throughout the organisation (Crowley, Burton, and Zolkiewski 2018; Baines, Ziaee Bigdeli, et al. 2020). Again, the feedback of a senior HeatCo decision-maker confirms these implications:

> [The modelling] forces you to have conversations you should have at the front-end of [a servitization] project. A bit of discipline in the decision-making process […] it helps engage sceptics and get on board more champions.

To create the strategic and operational insights and facilitate the shared understanding the CAS perspective and corresponding hybrid simulation offer, it is important to include a wide range of participants across the organisation in the model development. This not only enhances the quality of the model by ensuring that the diverse range of expertise is included but also contributes to the wider acceptance of the model (Ricciardi, De Bernardi, and Cantino 2020). Traditional approaches where models are developed by technical teams and then passed on to the wider organisation rarely create the shared understanding and buy-in expected.

The nested nature of the hybrid model provides the opportunity to consider different levels of abstraction, which enables different stakeholders with different perspectives and levels of expertise to engage with the model (Djanatliev and German 2013). Importantly, decision-makers need to recognise that the model development should be understood as a continuous effort that encourages different audiences to continuously engage with the model and reflect on changes in their understanding of their servitization journey and the implications for the service delivery system (Ricciardi, De Bernardi, and Cantino 2020).

5.3. Research implications

The study also provides significant contributions to servitization research. Most importantly, CAS is introduced as a theoretical lens to understand and investigate servitization. Servitization is currently investigated by detached research communities (Rabetino et al. 2018), which inhibits the widespread application of the available theories and methods. The introduction of CAS into servitization research provides a theoretical foundation for an integrated investigation of servitization, addressing the calls of several authors (Rabetino, Kohtamaki, and Gebauer 2017; Lenka et al. 2018; Rabetino et al. 2018; Sjödin et al. 2020). More specifically, the study shows how a CAS perspective provides the conceptual tools that can help address some of the core research challenges of servitization (e.g. service paradox, network orchestration and organisational learning).

In addition, the study introduces hybrid simulations into servitization research and, therefore, extends those studies that use individual simulation methods to investigate specific servitization issues (Wang, Breme, and Moon 2014; Asif, Lieder, and Rashid 2016; Rondini et al. 2017; Lieder et al. 2017). The present hybrid simulation (drawing on the strengths of SD, AB and DE) is proposed as a holistic approach to develop a CAS perspective on servitization that captures the operational and strategic levels and dynamic interactions which form part of a servitization effort (Brailsford et al. 2019). The research emphasises the importance of the interaction points between the simulation methods (Mykoniatis and Angelopoulou 2020) to theoretically and methodologically connect the short- and long-term perspectives of servitization.

5.4. Limitations and future research

Notwithstanding these diverse contributions, the study has some noteworthy limitations. Although HeatCo is a suitable company for this case study, the obtained findings are limited to a single case of HaaS, and the particular aspect of repair services. Also, the company is at an early stage in its servitization journey, focussed on understanding the possible implications of its plans, and other considerations may apply to manufacturers with a higher level of maturity of their servitization journey.

To make the results more generalisable, more testing and further validation of the applied hybrid simulation approach is needed. Also, due to HeatCo's relatively recent adoption of digitally connected boilers, the access and availability of field data was limited; but due to current digitalisation efforts, additional data will become available in the future. For manufacturers that have progressed towards conducting pilots, a wider range of data would be expected to be available and a wider range of specific points of enquiry would be fed into the model. Further, although HeatCo's B2C context is outside the mainstream B2B-focussed servitization research, it offers us the opportunity to investigate service delivery implications at a higher scale than pure industrial-focussed servitization cases would normally provide.

Despite these limitations, the study offers several concrete future research opportunities. The feedback from HeatCo's management shows the benefits hybrid simulations provide for informing its decision-making and it would be important for future research to investigate the utilisation of these to facilitate their adoption (by following similar considerations in Brailsford et al. 2013).

Further, the study shows the extent of time required for essential learning to take place to create the required service efficiency. Future research should explore how this learning can be accelerated and, specifically, how the principles of A/B testing (common in digital business contexts; Kohavi and Thomke 2017) can be applied to servitization and integrated into its simulations (von Rueden et al. 2020).

Simulation-based research approaches, at times, suffer from a lack of cumulative research tradition, as measures and models are individually selected and this limits the comparability of research findings (Banerjee, Morton, and Akartunal 2020). Considering hybrid simulations at an early stage in the formation of the servitization research domain creates an opportunity to establish clear guidelines (e.g. interaction points and core variables) from the beginning and, so, facilitate the formation of a cumulative research tradition that will accelerate the advancement of servitization research.

Notes

1. Although AB simulations cater for agent adaptability (Borshchev et al. 2014), these servitization studies consider agent behaviours, rules and properties as being static without making provisions for changes over time.
2. Rahmandad and Sterman's (2012) minimum model reporting requirements are met: a causal loop diagram explaining the conceptual structure of the hybrid model is provided (Section 3.2; Figure 1); simulation used AnyLogic 8 Professional 8.5.2, which allows the integration of multiple simulation approaches and interaction points.
3. The proportion of 10,000 boilers to 50 technicians, i.e., 200 boilers per technician represents the industry standards as provided by HeatCo.
4. Over an 18-year time frame the accumulated service costs lie between approx. £0.5 million (5y, 0% scenario) to £11 million (10y, 20% scenario) (see Appendix for service cost calculations).

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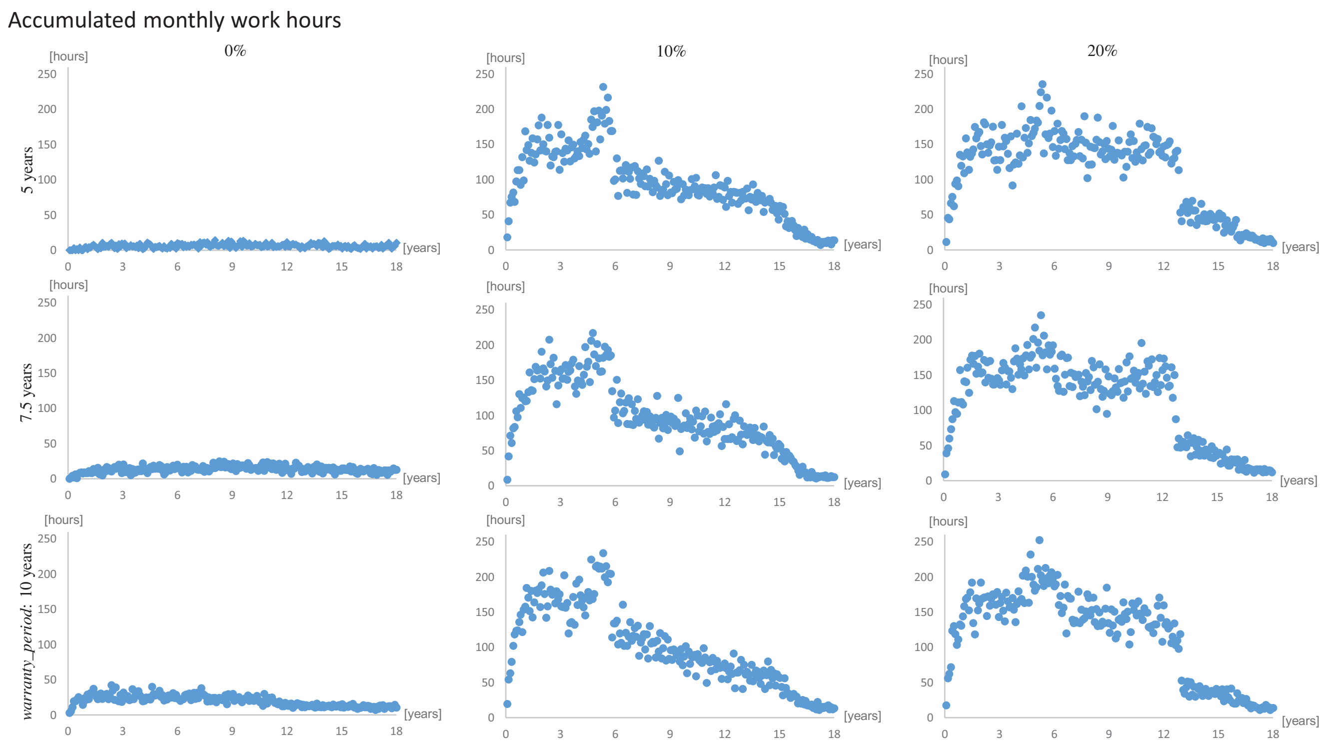
Appendix A. Work hours, simulation results of nine scenarios



In all scenarios, 0% HaaS adoption entails the least service work and 20% the most. The longer warranty period means there are more relatively old products in service, from the beginning of the simulated time period, meaning more additional work to be done even for the 0% scenario. The number of work hours serves as a performance measure which gives an indication of how capacity planning and resource allocation are affected by HaaS adoption.

The accumulated maintenance costs are based on a technician's hourly costs of £21.48.

Accumulated service costs of 10,000 boilers over 18 years	0%	10%	20%
5y	£573,746	£9,014,354	£10,767,961
7.5y	£1,277,374	£9,193,574	£10,884,984
10y	£1,913,941	£9,591,039	£11,266,727
Accumulated service requests of 10,000 boilers over 18 years	0%	10%	20%
5y	2679	11,622	12,732
7.5y	7225	13,399	13,914
10y	15,198	17,832	17,572