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Agile Methods on the Shop Floor

Towards a "Tesla Production System"?

Agile Methods on the Shop Floor

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Abstract

This discussion paper investigates two questions: To what extend can Tesla be regarded as a digital firm, and do we – as a result – see elements of a distinct "Tesla production system"?

While the EV-startup is widely approached as a competing automaker focusing on the electric drive train, which it certainly is, this paper argues that it can only fully be understood as a digital firm – a digital car company with a digital product embedded in a digital ecosystem. Its roots in Silicon Valley, its software-first approach, and its strategic exploitation of user activity data point into this direction.

In the second part, this paper explores to what extent Tesla's rootedness in software and its Silicon-Valley ancestry gave reason to introduce methods borrowed from software development on the shop floor. To a certain degree, concepts from agile software development found their way to the very assembly-line at Tesla.

Although it might be exaggerated to speak of a distinct "Tesla Production system", indications for a considerable and possibly enduring alteration of Lean Production paradigm can be determined.

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1 Introduction: The Rise of an EV-startup

Tesla Motors was founded in 2003 in San Carlos, California (USA) by two engineers, Martin Eberhard and Marc Tarpenning, who were later joined by today's CEO Elon Musk. The early years follow the playbook of Silicon Valley tech startups: Its founders made their money in the digital economy, and in the early years, Tesla relied heavily on venture capital funding. Since it was founded in 2003, Tesla has pursued the long-term goal to build cheap electric vehicles (EVs) for the mass market in large numbers. On each step, the money and experience necessary to affront the next step were to be gained, moving from top to bottom of the market, starting with expensive cars in small numbers followed up by ever-more affordable and accessible cars. Tesla Motors' CEO Elon Musk wrote in the company's blog in 2006 about the long-term strategy: "Build a sports car. Take the money to build a more affordable car. Use that money to build an even cheaper car. And at the same time make sure that there are charging options for emission-free electricity" (Niemeyer 2021, p. 34).

This plan is reflected in the history of the company: In 2009, Tesla's launched its first car, the 110,000 US$ "Roadster", a sports car manufactured by Lotus Cars headquartered in Norwich (UK). With this model, Tesla proved the concept of a performative and reliable battery-powered sports car. As of today, 2,450 Roadsters have been sold, mostly in 2012.

This model was then followed by Tesla's first full-production car, the luxury sedan "Model S", an all-electric luxury sedan and the first vehicle developed from the ground up by Tesla and built entirely in-house in Tesla's firs own factory in Freemont (CA). The car collected awards, like Motor Trend's "Car of the Year", and outperformed competing models– according to industry experts (Matousek 2019). The model put Tesla on the map as serious contender in the luxury segment, especially in the United States. Up to date – the model is still in production – Tesla has sold over 250.000 units of the Model S.

In 2015 the production of "Model 3" was powered up, a more affordable upper middle class sedan. In 2018 Tesla reached a production volume of 5,000 cars per week. This achievement was acknowledged throughout industry at the time, and considered a watershed moment for the company. The achievement of this self-imposed goal, albeit just barely, is said to have led the auto industry to take Tesla seriously for the first time as a competing automaker. In 2021, Tesla ranked as global leader in electric vehicle production after selling approximately 936,200 units. Tesla hat become the world's biggest manufacturer of EVs, with annual growth rates around 50 % (Carlier 2022).

Tesla is the first American car maker to enter the stock market since the Ford Motor Company in 1956. By the end of 2021, Tesla reached a valuation on the stock market of over a trillion US Dollars, making it for several weeks the most valuable company in the world. At least in terms of market capitalization, Tesla has since enjoyed the proximity with Amazon, Alphabet, Apple, Facebook, and Microsoft – the leading companies of digital capitalism, its value at the stock market still by around an order or magnitude above the ones of traditional auto makers. As the aforementioned Silicon Valley companies, it shares roots in the venture-capital-driven startup scene in California, the share the spirit and sometimes megalomaniacal mission to make the world a better place – in the case of Tesla "to accelerate the world's transition to sustainable energy" ("About Tesla" 2022).

Tesla has become the prime innovation driver for the automobile industry, and the pacesetter for the global transition to battery-electric vehicles. Tesla's innovation in the sector is mainly noticeable in three main areas: the product, the role of the customer, and the production process itself. Tesla became a pioneer of a “digital-industrial hybrid sector” (Valentin 2019, p. 7) and can be described as “a digital company that happens to also build cars” (Daum 2018). Andreas Boes and Alexander Ziegler write on Tesla: “With the Californian company, a competitor has established itself on the market that operates in automotive with the new business models of Internet companies” (Boes, Ziegler 2021, p. 5).

2 Exploiting the Digital

The term “digital firm” was introduced in 2009 by Kenneth and Jane Laudon in their work on management information systems. They defined it as “an organization that has enabled core business relationships through digital networks” (Laudon 2006). From a more critical perspective, the analysis of digital companies as representatives of “digital capitalism”, a term coined by Dan Schiller, lead to an understanding of the digital economy as distinct mode of value creation (Schiller 1999). Its key operations can be summoned with Evgeny Morozov’s term “data extractivism” – a strong analogy to fossil extraction portrays business models evolving around user data creation and their exploitation with the help of algorithms (Morozov 2016). Digitization has created a powerful new type of company whose business model is based on platforms. Especially tech companies have embraced the operation of internet-based applications and infrastructures following the platform model, which became center-piece of their monetarization activities.

2.1 Platforms and digital ecosystems

Key mechanisms of platform capitalism according to Srnicek are primarily the development of proprietary platforms and ecosystems, the cross-subsidization of free services, and the exploitation of network effects and user activity on those platforms (Srnicek 2018). According to Seemann, the platform constitutes a new form of social organization, marketplace and public space at the same time (Seemann 2020). Platforms have become – so to say – the factory of digital capitalism (Daum 2017). Although not replacing traditional industries and factories, they became a “sectoral mode of accumulation” (Lüthje 2016), characteristic for capitalism in the era of information. The applications of algorithms and data extracting technologies have become the centerpiece of digital capitalism’s mode of value production.

Corporations in the digital economy tend to strive for building of platforms or ecosystems, pursue a monopoly in their field, and try to keep their users locked in. Their actual or envisaged potential for scale – the world’s entire population being often the ceiling of their efforts – invite a constant flow of venture capital, resulting in exorbitant stock market valuations and enormous liquidity. Their valuation comes mainly not from tangible assets but from their user base and future prospects, especially through the promise of market domination.

Traditional firms in every sector of the economy are shifting towards cloud and software driven operations, and are at least in part adapting features and aspects of the culture of digital firms. Ziegler describes how the *modi operandi of “the internet economy find their way onto the strategic agenda of industrial companies”, resulting in “the contours of a new type of industrial company for an informatized mode of production” to emerge (Ziegler 2020, p. 289).* Valladão calls this vision the “virtual conveyor belt”: “A production process linking real-time online monitoring of its customers, Big Data treatment, and interactive information flows from manufacturing components" (Valladão 2014). The effect is two-fold: The application of internet-centered technologies in industrial manufacturing, accompanied by efforts by the involved firms to transform themselves into companies pursuing digital value chains.

In the following, I will focus on three theoretical starting points which describe mechanisms that digital firms have developed in their pursuit of economic success. These are the exploitation of the information space, perpetual innovation, and the hybrid user. I consider their presence to be crucial for the understanding of the paradigm shift that Tesla introduced in the automotive industry.

2.2 The information space

In what Karl Marx described as "big industry" (Große Industrie) the exploitation of wage-labour in the "direct production process" is central to both production and value creation (Marx 1865, p. 469). While this was central for industrial capitalism, in recent years, industries have embraced digitalization, the Internet of Things and internet-related business models. As a consequence, these firms shift into the realm of information, data and networks, the "information space" (Boes 2005). The shift to information as center-piece of value creation has a profound impact on the results of the information-determined production process. The more it becomes defined mainly by its information content, the less meaningful the processes characteristic for "Big Industry".

In Boes' and co-workers' view, the conquest of the information space becomes a "motor" for a new historical form of accumulation embedded in "a new phase of globalization" (Boes et. al. 2012, p. 28), which is characterized by "informatization as a central part of the development of social productive forces“ (Boes, Kämpf 2012, p. 317). According to Boes, the Internet constitutes the base technology for the information space, "which becomes a new kind of "social space of action". This is regarded by the authors as "a fundamental leap in the development of productive forces in society“ (Boes, Kämpf 2012, p. 325). Boes writes: "For the first time in human history, it is possible to make people's general use of information 'connectable' to complex information systems in a common medium" (Boes 2005, p. 221).

The revenue model of internet companies in fact constitutes a model for the "economic exploitation of the information space" and thus "a new paradigm of value creation“ (Boes, Ziegler 2021, p. 15). Andreas Boes also speaks of a "new production system", with regard to the way in which internet firms act. The shift from the production of large numbers of identical tangible objects towards informed objects, objects with a considerable portion of information, create "an open space of possibilities for completely new applications, within which objects linked to the information space, such as the automobile, can change their character" (Ziegler 2020, p. 286). Boes' concept offers a notion for the degree of industrial players embracing of data-extractivist mechanisms and business models in an attempt to mimic tech companies.

2.3 Perpetual innovation

In the information economy the production of identical copies of the same commodity becomes increasingly nonsensical, thus only *new* information *is* in fact information. Additionally, it becomes ever-harder to secure the private use of such information. Therefore, as Morris-Suzuki pointed out, it becomes increasingly "difficult, if not impossible, to maintain monopolies of information indefinitely, and there is a perpetual tendency for privately owned information to flow back into the public domain" (Morris-Suzuki 1996, p. 62).

This fundamental property of information changes the way innovation functions in capitalism. Was it once a necessary but exceptional method to streamline production, to outperform the competition, its role now changes profoundly. In an increasingly information-focussed economy, the creation of new information becomes also the main source of surplus value. The “design of new productive information“ becomes essential and enters the core of a company’s profitable activity (ibid., p. 63). The exploitation of manual labor in the “direct production process” (Marx 1863, p. 4) thus loses relative importance, and innovation takes on a new meaning. Occasional leaps in innovation are replaced by a continuous ramp-up – the exception becomes the rule.

This results in a “perpetual innovation economy”, where “surplus knowledge” is constantly generated leading to the “incessant generation of new products and new methods of production” (Morris-Suzuki 1996, p. 60). The consequence of this situation is the generation of an ever-changing product, a product which is constantly and continuously modified in order to stay ahead of the competition. Boes and Ziegler make a similar consideration, when they state that one key principle of the proper use of the “information space” lies in the “transformation of data into innovations as the engine of permanent innovation” (Boes, Ziegler 2021, p. 17).

2.4 Dual use products, and hybrid users

A fundamentally new source for such a perpetual innovation – this being one of the core inventions of digital capitalism – constitutes the very customer or user or client himself or herself. For data-extractivist operations of platforms, identification of the user and the constant monitoring of its activity are essential for the operation of the service. All platforms are eager to engage their “prey” and to keep them continuously engaged, stimulating them to generate a stream of activity data that never runs dry. This is mainly achieved via tracking technologies on websites, and creation and maintenance of user profiles. The exploitation of the end-user of the very product gains importance, he or she finds him- or herself in an ever-tighter feedback loop between use and update. In “user-generated capitalism” (Daum 2017), consumption becomes production, the consumer a producer.

As a consequence, users find themselves in a “hybrid state” (Crawford 2021). As Crawford showed in her analysis of AI-driven products such as smart home devices or artificial language assistants, users take on several roles while using the product or service. They are users of an application or device, and subsequently customers of the firm, which results in the build-up of an ever-sharper and richer user profile. This profile can later be monetized by the platform vis-à-vis third parties. But a third role of users or customers emerges, too: In the course of the interaction, they produce new information like (voice) commands suitable for training the AI algorithms at the very core of the system they are using. »This combination of consumer, customer, worker, resource and product is something completely new«, Crawford emphasizes (ibid.).

Users perform unpaid work by communicating, correcting and steering the application or service. They become an active part in the life cycle of products as they are incorporated into the process of further improving and developing the very products they are using, they involuntarily become part of closed-loop engineering processes. This leads to products themselves becoming also hybrid, or – as the sociologist Peter Schadt puts it – commodities of “dual use” (Schadt 2021, p. 33). By generating data while being used by the customers, these data then trigger updates of the very product itself or constitute the basis for new products, which the company can make profitable. Such products develop a double functionality; they are not just products, they become in fact also means of production.

3 Tesla: Tech Company or Car Manufacturer?

In the light of the theory – can we make a case for Tesla satisfying the conditions of a digital firm, establishing a platform-model ecosystem, a tech company exploiting the information space, a permanently innovating company using their customers as resource for continuous improvements of the very product itself?

In order to answer the question, and after having established some criteria for a digital firm, the following chapter tries to present evidence for Tesla to meeting these criteria, based on economic data, and the evaluation of industry experts' assessments.

3.1 Tesla's "Internet Communications Devices"

Tesla's product is not just a traditional car with an electric drivetrain; it is designed differently from the ground up: At the center is a high-performance computer running a self-developed operating system. The central computer controls all functions of the automotive hardware. Software updates and maintenance of the software are done over the air or as remote maintenance, as we are used to from other digital devices. As opposed to that approach, traditional automakers to this date part from an engineering perspective, and build the car around an engine, regarding software functionality as extras and add-on enhancing the core product, which is mainly defined by its hardware.

When introducing the iPhone to the world in 2007, Apple CEO Steve Jobs famously referred to it as "internet communications device" (Protectstar 2013). By doing so, he pointed at the main innovation the iPhone represented as opposed to the so-called smartphones of the time: The iPhone was designed not as a telephone with internet connectivity and a touch interface, but an internet-first device that could also be used to make phone calls. The same can be said about Tesla's "mobile devices" – they are, in fact, mainly "internet communications devices" that can also be driven around with. As of today, phone calls facilitated by a telephone company have almost entirely been replaced by numerous apps, and the corresponding business model almost died out.

3.2 Tesla as a platform ecosystem

Tesla was the first automobile company to treat internet connection of its vehicles as of central importance. Since in-house assembly started in 2012 with the Model S, all subsequent cars have been in constant connection with Tesla's servers via the Internet ("Tesla Model S" 2022). The attempt to harvest customer data, e.g. their charging behavior, usage patterns and driving data sets Tesla apart from other car manufacturers. A former Tesla executive states, "the basic idea is to make money like Apple does with the App Store". And automotive consultant Steffen Gänzle agrees: "The platform model is the real danger for the competition" (Freitag, Rest 2022). While Tesla's entertainment system already allows third-party applications to be used as web-apps, like streaming services, it has not yet built an app-store that would allow the installation of native third-party app. But according to Sawyer Merritt Tesla is in active development of an app store for its vehicles (Schmidt 2022).

Tesla has been consistent in designing the car around a central computer with an operating system with as few components as possible and ensuring short communication paths. The process of opening the car by the driver illustrates this: The car can only be opened via smartphone with a user properly registered and logged on to Tesla's platform. This is convenient for the driver – no keys needed – and establishes the connection between the Tesla owner and Tesla's data centers even before the ride begins. A software-centered approach is taken here well-established in digital devices with their operating systems, app stores and update functionality and also standard operation – but mostly remains uncharted territory for the auto industry.

Tesla decided early on not to rely on public or third-party charging infrastructure, instead it built its own proprietary network from scratch. To date, Tesla owns and operates the largest fast charging network in the world with more than 36,165,000 chargers in 3971 stations (“Tesla Supercharger”). They are constantly connected to Tesla’s servers, enabling the company to remotely monitor their status (free, occupied, reserved, and damaged). Same applies to the status of approximately two million Tesla vehicles on the road (charged, location, planned route etc.). Additionally, Tesla offers by far the smoothest user experience in charging (“plug and charge”): After plugging in the charging cable, an automatic handshake takes place, the charging station recognizes the identity of the car or rather its owner, resulting in a smooth process accustomed from digital devices like mobile payments. This ecosystem approach contrasts with the view and subsequent strategy of traditional car companies – they don’t get their hands dirty with the supply of combustible material.

Tesla offers a travel route planning application and suggests charging stops like any other EV manufacturer. Based on the real-time location data of all of its customers, as well as their batteries’ charge level they can provide an optimized route. This knowledge gives the company an advantage over third-party solutions or public charging infrastructure, where neither the user nor the car-company has access to real-time data, let alone expected occupancy in the future. Tesla’s experience with the global supercharger network of charging stations resulted in a technological lead in the field. This is key for the usability of the product, and a prime example for the competitive advantage a fast scaling first mover can obtain exploiting network effects.

The electricity ecosystem goes further; Tesla is a manufacturer of solar panels, and a systems provider for home storage solutions for electricity. Tesla has been active in the market for storage batteries and photovoltaic systems, since 2015, when the “Powerwall” was launched. Tesla recently intensified its activities in the electricity market and is increasingly becoming an electricity producer and trader (“Große Energiekonzerne” 2021).

Tesla’ attempts to be as Internet-centric as possible, also led them to renounce traditional distribution channels, mainly through third-party vendors and a network of dealerships. In contrast, Tesla’s website is the main vending portal for the products, and the cars can be and must be configured and ordered online. The online portal is accompanied by brick-and-mortar showrooms, where the cars can only be examined and test drives can be scheduled. Not only do they omit dealership – a move which was even illegal at first in some states in the United States –, the same happens to contract repair shops. Combined with the fact, that EVS need much less physical maintenance (no oil exchange, virtually no brakes etc.), the necessity to visit a repair shop in regular intervals becomes no longer necessary (McKenzie 2019, 58).

Management consultancy Morgan Stanley calculates that today only half of the Tesla value is based on its core business. In an enterprise value estimate based on a “sum-of-the-parts“ method, in which different areas of a company are evaluated separately in order to arrive at an overall evaluation, Morgan Stanley concludes that “network services“ accounts for 30 percent of the rating, while “mobility/ride-sharing“ for 7 percent, “Car“ for 49 percent, insurance for 3 percent, “parts supplier“ for 11 percent (Powell 2020). The rest is to be provided by the additional business like digital solutions and mobility services.

Individually customized insurance policies constitute a further business model enabled by the exploitation of the “information space”. Tesla’s vast amounts of individual user data enables it to offer insurance with premiums calculated solely on the basis of the individual customer's driving behavior in the past (O'Kane 2021). This capability is out of reach for the insurance industry to this date, mainly due to the lack of the necessary amount of data – Tesla being the world first to offer such a service.

3.3 Tesla's over-the-air perpetual innovation

Tesla was the first auto manufacturer to ship production vehicles, i.e. mass-produced models equipped with an operating system capable of over-the-air updates (OTA). OTA updates constitute a method of transferring software updates to a mobile device – usually via Wi-Fi or mobile data transmission. Tesla included over-the-air updates to its software with the introduction of the Model S in 2012. Previously, the method has been used primarily for uploading new firmware to smartphones.

Tesla's software-centered approach gives it a tight grip over the vehicle, even if it is in possession of the owner. Tesla is able to remote control the vehicle, e.g. assigning different ranges or capacities to the battery according to the customer's current subscription (within technical possibilities). This is possible due to the fact that different ranges of the battery, as well as different levels of driver assistance are software-controlled (Usborne 2017).

The user or customer plays an important and somewhat unusual role for the company. Customer relations change, partly because of the properties of the product, partly due to the firm's approach to them, and last but not least because the typical Tesla clients are also well distinct in their habits and desires. The customer shifts form one buying a finished product (sell and forget) to one who is accustomed to receive an unfinished, raw beta version of a product or service at first, which during consumption or use morphs, updates itself, keeps pace with development, surprises with new or improved features – just like a smartphone user would expect it.

Few car companies deliver software updates for their vehicles, and if they do, it tends to be once every year or two. These updates have to be installed at the dealership and often only fix bugs rather than provide new features that increase customer satisfaction. With the increasing use of computer technology in vehicle construction, the technology is also being used more and more frequently in automotive. Tesla uses this as an advantage to push innovation. With Tesla's operating system version 8.0, over 200 new features were delivered, including temperature monitoring when the car is parked for a long period of time, a new media player, and autopilot improvements (Lawley 2016).

In contrast, for traditional manufacturers, constant updates, fixes and micro-improvements are culturally a no-go. For traditional automakers, the product history is mostly completed once the car is sold to the customer. Steven Denning argues: "What the customer got on the day of purchase is what the customer got to use for the rest of the car's life. The customer wasn't asking for anything more" (Denning 2020b). In their mindset, a car is manufactured in perfection, and afterwards remains ideally unchanged, the only goal of maintenance being to preserve the original state and condition. They see updates, bug fixes, slight changes primarily as a cost factor, a resource hog, a threat to the normal course of things. For Tesla – like for any other software-inclined organization – updates are necessary and accustomed self-evident elements of daily operations. Tesla delivers regular updates, some of them beta versions so that the vehicles can then be improved during operation through user feedback. The improved version is then included in an upcoming update.

3.4 Tesla's crowdsourced innovation

A prime example for Tesla's crowd-sourced innovation is the strategy around autonomous driving functionality, or "Full Self Driving" (FSD) in Tesla's broad-shouldered labelling. Tesla has become a front-runner in advanced driving assistance and autonomous driving without hardly any research staff and testing operations in that field. The FSD-team comprises of “more than 1,000 people” in 2021, according to company sources (McFarland 2022). Since 2012, new vehicles have been delivered with the sensors required for autonomous driving and an on-board computer for processing them. Additionally, while driving the cars, all users use either some kind of different beta-versions of autonomous driving capabilities or simply drive themselves with cameras and sensors engaged – resulting in the generation of test-data for the optimization of the very system they are using.

Tesla currently offers three levels of Autopilot: Autopilot (standard), Enhanced Autopilot and Full Self-Driving Capability. The base package comes with Traffic-Aware Cruise Control, which adapts the vehicle‘s speed to that of surrounding traffic, and Autosteer, which assists in steering “in a clearly marked lane“ using Traffic-Aware Cruise Control. Enhanced Autopilot adds Lane Change Assist, Navigate on Autopilot (Beta), Autopark, Summon, and Smart Summon. The “Full Self-Driving Capability“ also offers a traffic and stop sign assistant (beta) and should also include a city steering assistant “in the near future“ (“Tesla FSD Beta” 2022). All variants require active monitoring by the driver and are therefore Level 2 systems. The system is Level 2+ in the US, where the FSD Beta can be tested without hands on the wheel.

Upgrades and improvements are delivered as an update long after the product has reached the customer. To use the functionality, an initial payment of 10,000 US $ is due. Additionally, a monthly subscription fee of 99 US $ is due (“Tesla FSD Beta” 2022). Currently, 7 percent of Tesla owners did activate FSD in the USA (Goreham 2022). Customers test the beta version of the software on the fly and deliver training data to Tesla‘s server in real time. “It collects data from hundreds of thousands of cars” (Krachten 2021, p. 164). Tesla has now more than 100,000 people in its Full Self-Driving Beta program (Lambert 2021).

The company records individual driving behavior, edge cases, and rare encounters. Compared to professional test drivers or simulations, this machine learning method is much cheaper. Starting from this real-world data the development team can focus on fixing the recorded bugs. Finally, after a certain period of time, the new update is ready which includes all learnings and improved functionalities, and the crowd-sourced innovation circle closes. This way, the company can – for instance in the case of complaints by users or regulators – bug-fix their already deployed software within hours on the entire existing fleet of around two million cars.

Tesla is so able to both reassure the customer relations and feed user behavior back into the innovation process. Tesla’s beta testing drivers become – and apparently willingly so – hybrid users as described by Crawford (2021). This results in an ever-morphing, continuously updating product. Similar to any internet platform records the user’s activities – surfing, texting, clicking, watching, the Tesla platform record’s the driver’s activities while the car is in use. In developing certain capabilities of its devices, the company relies on the principle of constant user-driven innovation.

4 Agile Methods: From Bits to Atoms

In the following Chapter I ask the question: If Tesla is a digital firm – should this characteristic also be reflected in the firm's approach to hardware engineering and manufacturing? Does Tesla transfer development methods from software to hardware? Have agile methods, while standard procedure in software production, crossed the firewall into the realm of hardware development at Tesla Motors? And if that's the case, does this constitute elements of a possibly distinct production system at Tesla that modifies or even transcends established paradigms in the industry, namely the Toyota or Lean Production System? The answer to these questions encounters some difficulties, due to the lack of reliable sources and scholarly work on the subject. Little is known besides the attempts at Tesla and Volvo mentioned by Denning (2020a). I will first briefly introduce agile methods, a standard development framework for software development and creative processes and its use in the automotive industry.

4.1 Agile methods

Agile methods become standard operations procedure in software development in the shape of various agile methodologies (The Agile Manifesto 2001, Sutherland 2014, Layton, Ostermiller 2017). Agile processes encompass small teams developing functional prototypes in short iterations, while constantly communicating and largely controlling themselves. Usually every two to three weeks, an executable intermediate product with clearly recognizable development steps (product increment) has to be completed. Change requests during the lifetime of the project are not only allowed, but welcome (Stellman 2014).

Since the publication of the Agile Manifesto (The Agile Manifesto 2001), its principles have become standard operations procedure in software development in the shape of various agile methodologies (Sutherland 2014; Layton, Ostermiller 2017). These methods replaced almost entirely models framed as "waterfall" with its linear sequence of project steps based on detailed specifications (Daum 2019, p. 27). Agile in contrast uses very sparse documentation, and user needs are expressed in terms of "user stories", and the software developers and product managers talk through what the user is trying to accomplish. Testing becomes part of the development process and is performed in parallel with the development (Denning 2020).

In the last decade agile methods have established themselves as a new "production model" at industrial scale in software development. This includes the synchronization of dozens or even hundreds of teams with frameworks named "Agility at Scale" (Denning 2018) or "Scrum of Scrums" (Agile Alliance 2015).

Agile methods until very recently were limited to software development. Nonetheless, we see evidence for a spillover of agile methods over from the software-engineering to non-software areas of production, too. And it's worth noticing, that before agile methods became popular, the waterfall model reigned supreme in software development, too. Most developers familiar with the old system couldn't possibly imagine a different "best way" of doing things in their field of expertise.

There's little to none academic writing on the subject of agility in manufacturing and hardware engineering, with rare exceptions (Hejaaji 2014, Youssef 2017, Ikonomov 2020, and Blokdyk 2021). Although still – both on the shop floor and in the literature – a rare phenomenon, some sporadic evidence can be found for their hardware-centered use, namely in prototyping, especially in the maker movement context and in connection with 3D printing (Accialini 2022). For manufacturing at scale no traces of actual application can be found, let alone in well-established industries like automotive.

4.2 Agility in manufacturing?

As Steve Denning points out, the industry is widely convinced that, what might work in the software area, won't work on hardware. Bits are not atoms, after all (Denning 2018). Denning argues that hardware developers need to embrace agile principles to keep up with the pace of innovation: "Yet as physical products and services are increasingly software driven and the 'Internet of Things' makes its presence feel, the distinction between software and manufacturing is disintegrating … thus accelerating the spread of the agile paradigm" (Denning 2018, p. xviii). For Denning, the central truth about the slow pace of automotive innovation consists in: "a leadership and management problem, not a problem of atoms versus bytes" (Denning 2020b).

As many a management guru has lamented, traditional ways of doing things are embedded deeply in the majors' corporate cultures, and so are outdated definitions of their products. Canzler and Knie emphasize as an additional hindering factor an attitude of sectoral inbreeding in the industry: "The industry develops its own criteria for success in mutual professional consensus. Critics disparagingly refer to this tendency towards uniformity, which again and again leads to self-stabilization, as 'inbreeding engineering'" (Canzler, Knie 2021, p. 209). In the authors' view, traditional automakers refuse the very principle of trial and error, for them it is "not acceptable". For "car companies are still thinking of a car as a metal transportation device with a few electronic gadgets attached to it," they have a hard time embracing methods popular in the software world and creative industries (Denning 2020b).

In contrast, Steve Denning expresses his conviction that Tesla and SpaceX "demonstrate that it is possible to run a hardware company like a software company in an agile fashion" (Denning 2020b). Canzler and Knie support this. In their view, with new contenders "trial and error replaces peer-to-peer assessment. There is spontaneous consideration, conceptually quick translation, repeated reprogramming, immediate testing and then discarding. The central point of reference is not the specialist board ("Fachkollegium"), but […] the end user of the products (Canzler, Knie 2019, p. 461). Andreas Boes and Tobias Kämpf go so far as to designate a general trend in engineering: "This new production model has established itself across the board in the software industry and is now also becoming the new guiding principle in classic engineering work" (Kämpf 2018, p. 521).

If the industrialization of software now spills over to hardware too under the flag of agility, possibly challenging or modifying existing standards, like the Lean Production paradigm in the automotive industry – can evidence for this asserted tendency be found at Tesla? In contrast to traditional auto makers, Tesla had no need for profound cultural and organizational changes triggered by digitalization – it already parted from a genuine startup-culture, with a strong focus on software. Agile methods seemed to be the go-to model from the very beginning, rather than posing a challenge for an overdue organizational change.

Quebec-based researcher Michaël Valentin proposed the term "*Teslisme" for a new iteration after Fordism and Lean Production.* Valentin, associate Director of the consulting firm OPEO, proposed a model interpreted as successor to Toyotism, responding to the challenges of digitalization and "as a potential organizational model for the Fourth Industrial Age" (Valentin 2021, p. 57). Essential principles according to Valentin are e.g. "hyper-manufacturing", replacing the "right first time" principle at the heart of lean manufacturing. It calls for ever greater agility in the implementation of testing and learning approaches (Valentin 2019, p. 41). "Cross-integration" and "software hybridization") on the other hand point at the harvesting of digitalization in manufacturing, which allows "condensing the value chain, decompartmentalizing businesses and innovating disruptively" (Valentin 2019, p. 69). According to him, the new model constitutes "a connected, agile model, capable of disruptive innovation and attracting talent, but also capable of ensuring the balance between the acceleration of technological progress and the pace of skills development" (Valentin 2019, p. 33). Valentin summons the debate on the characteristics of each industrial phase: disruptive technological progress, new needs in society and an appropriate organizational model.

4.3 Tesla, first principles, and the Giga Press

Especially in the early days, Tesla operated like a small cross-functional startup. Automotive journalist Edward Niedermeyer described the work environment at Tesla headquarters at Stanford in 2014 as follows: "The office's open floor plan was unlike anything I had seen at an automaker, with PR people sitting next to engineering workspaces covered in mechanical and electrical components…. It was a vibrant and unpretentious environment whose layout and youthful staff spoke to the flat structure and collaboration of a software startup. (Niedermeyer 2019, p. 4). Still today, Tesla employs a relatively small number of software engineers, according to one source: "Tesla has 100 hardware engineers, 200 software engineers […] as of 2020" (Wise 2022). That's a comparatively small number; Volkswagen employs 5,000 software engineers in the Cariad software branch alone (in May 2022) while aiming at doubling this figure in the near future (Riering 2022).

And the first vehicles built where all but flawless – phone key issues, panel gaps, road noise problems, unreliable falcon-wing doors with early Model X, Tesla Model S door handle issues – to name only a few – were omnipresent in the early stages of every model's production ramp up. Tesla had received criticism for its poor body shop and welding, gaps and unnecessary amount of welded sheet metal parts (Johanson 2020). As a reaction to that, apparently Elon Musk came up with the idea of producing the entire body using die-cast technology, inspired by a toy Tesla parked on his desk. According to the legend, "he thought about the 'limits of physics' with this technology. There was none" (Freitag, Rest 2022).

Aluminum die-cast has been used for components and chassis parts for decades, but mainly for smaller parts, not for the entire body or large parts of it. For the body, sheet metal shell constructions are the standard method. Although consisting in fewer parts, a lot of welding has to be performed on these. Since the summer of 2020, Tesla's plant in California has been using the world's largest high-pressure aluminum die-casting machines. The machines weigh 420 tons and generate a clamping force of 6000 tons. Die-casting of very large parts is a technology developed by Italian manufacturer IDRA, and also in place with Tesla in Shanghai and in Berlin. Tesla has developed a special aluminum alloy that makes this possible (Financial Literacy 2020, Tmio Tesla 2021).

The entire rear half of the car is now cast in one piece (Ruffo 2020). A single aluminum component replaces around 70 parts that were riveted, welded or glued together, a complex and time-consuming process that consumes a lot of energy and time on the factory floor and is a source for mistakes, fluctuations, and imprecisions. The die-casting cycle lasts 90 seconds, theoretically producing 1.5 million Model Y vehicles per year in Berlin. According to experts, the Giga-press will save 300 assembly robots, reduce manufacturing costs by 40 percent and reduce the required factory space by 30 percent. This is just the beginning of a new push towards automation, as a result of which the front module of the vehicle and the battery socket are expected to also be produced in just one piece (Evannex 2022).

The Giga Press is a key innovation in Elon Musk's arsenal to lower the cost of the Model Y and achieve production numbers that target meaningful market share (IDRA Group 2021). Even in the actual core area of car manufacturing, Tesla is setting new standards. German casting expert Wolfram Volk from the Technical University of Munich sees the potential for giga-casting to "re-invent body construction".

So, do other manufacturers have to follow suit? Several manufacturers such as Volvo or Chinese startups are now using the Gigapress (Carney 2022, Bork 2022). Rumors have it, that Volkswagen plans to follow Tesla in this regard and install Giga presses in their projected new plant in Wolfsburg to accommodate the Trinity project (Reuters 2022). According to an analysis by the investment bank Bernstein, by 2030 every second electric car will be manufactured using this process (Freitag, Rest 2022). Prof. Wolfram Volk, former head of the Chair for Forming Technology and Foundry Engineering states: "With the greenfield approach, as propagated by Tesla in Brandenburg, for example, the OEM can save significant space in body construction for its electric vehicles. With a view to the brownfield, on the other hand, it is important to consider whether aluminum giga-casting makes sense" (Fuchslocher 2022).

The development of entire parts casting, although in itself not a new technology, seems to be a clear indication for "thinking outside the box". Although not related to agile processes, it is in fact an application of "first principles", one of the guidelines at Tesla's. Often attributed to Physics Nobel laureate Richard Feynman (2011), it consists in rejecting reasoning by analogy, only taking the laws of Physics for granted, while inclined to jettison industry conventions and ways of doing things in favor of a fresh approach to engineering challenges.

4.4 Agile principles at Tesla

Joe Justice, author of the book titled "Scrum Master" (Klein, Justice 2021) and former lead of Agile at Tesla, gives some insights into Tesla's Freemont factory, where he operated Agile@Tesla in 2020. In his reports he gives a vivid description of the plant's daily operations at that time. According to Joe Justice, Tesla approaches functional improvements in short cycles by independently acting teams. Plans are periodically revised, and incremental product improvements are produced in quick succession. According to him this is standard operation for security and very small feature releases: "Tesla makes 27 changes in production per model per week" (The Agile Wire 2021).

So-called pilot lines or lean cells take on traditional manufacturing tasks e.g. the insertion of a heat pump. Their task is also to improve the component and the assembly procedures on top of the group's tasks in the assembling process. "Design and production are the same", claims Justice, "The install team IS the R&D team, full stack". Testing of new components does not happen in separated R&D departments, but on the very assembly line itself. This leads to – according to him – astounding testing-to-in-production times of hours, instead of years (Justice 2021). Krachten supports this statement when he notes that Tesla has adopted Apple's concept of "design for manufacturing," characterized by rapid prototyping: "During the development process, manufacturing issues and design are constantly aligned" (Krachten 2021, p. 189).

Justice gives the example of a customer rejecting a car somewhere around the world due to a poor paint job, which raises red flags on employees' phones. "Bad paint, the customer complains. Red flag on every phone. The paint has flaws. Build a mob, walk up, and understand in 5 minutes how to contribute" (Justice 2021). The term mob programming refers to a technique in software engineering, which consists in a software development approach where the whole team works on the same thing, at the same time, in the same space (Pearl 2018). This technique from the software world has its sibling in the Toyota Production System. Genchi genbutsu ("go and see for yourself") or "management by walking about" is one of its core principles according to Hagirian (2021, p. 67). It suggests management personnel to immerse themselves in their company's daily operations and have direct knowledge of the production site or business section.

4.5 Tesla: Test Driven Development

Testing plays a major role in software development, it is usually time- and resource-consuming, to the extent, that programmers often quote a 20/80 rule-of-thumb, referring to 20 percent actual coding time and 80 percent bug fixing time. In the classic (waterfall) approach, testing took place as a phase shortly before implementation and well after production, resulting often in a bottleneck and posing a challenge from a quality perspective. In the agile approach, testing is therefore integrated in the software production process itself.

Test Driven Development (TDD) is a strategy well-established in software development that guides the development process of software using various tests. Instead of testing products well after assembly in a separated stage (post-processing), in TDD test cases are part of the software design from the very beginning. Test routines are written and implemented even before the corresponding software solutions are tackled. The software itself is programmed precisely to pass that very test ex-post. Kämpf writes: “In digital development environments, the software code is continuously (often daily) automatically tested by all teams and combined into a common software product” (Kämpf 2018, p. 521).

At Tesla they embrace this principle, having established a process of software and hardware self-testing called “factory mode”, resulting in a “very fast feedback loop with automated DevOps tests”, covering all non-destructive tests for every single car automatically (Unusually Well Informed Podcast 2021). DevOps are methods that combine software development (Dev) and IT operations (Ops) with the aim of providing continuous software delivery with high quality, thus shortening the system development life cycle (Freeman 2020). Testing in a DevOps environment is a continuous and automated process that enables continuous and faster delivery of software. Testing spans every phase of the Software Development Lifecycle (SDLC).

Every few months a major release is launched, similar to the procedure with software companies. This allows Tesla to quickly make design changes and optimizations to current models. There are updates and bug fixes not only for the software every few months, there are also constant interventions in the production of the current models. This means that subsequent vehicles of the same name and model are considerably different. These “liquid specifications” result in cars of the same make and model that are different, posing challenges from a certification and type approval standpoint. It leads – in extreme cases – to the necessity of testing every single car. According to Justice, “single-car testing actually takes place: “When every car can autonomously put itself through every homologation and certification test, that is not destructive, every car can be different“ (Justice 2021).

This is possibly the most distinct feature in contrast to the Toyota production system, which aims for fixed specifications. As auto industry expert John McElroy puts it: “Under the Toyota doctrine, design changes introduce variability, and variability leads to quality problems” (McElroy 2021). Usually it takes two years in the industry until the first design changes get a chance to being implemented. As opposed to the Toyota model with its two to three years implementation time between first designs and implementation in actual production, Tesla makes design changes almost on the fly. McKenzie states, that “Tesla has a philosophy of ‘continuous improvement’ in the manufacturing process, which means it continues to develop its vehicles long after sales have started” (McKenzie 2019, p. 191).

Kyle Field calls the agile development for factories “extreme manufacturing” (Field 2018), referring to “Extreme Programming”, a software development method, which mainly consists in bringing together two people to closely work on the same task in close proximity and simultaneously (Beck, Andres 2012).

4.6 Confirmation from disassembly

Can we see the claimed continuous improvements in the final product? A source in relation to that matter are the reports of companies, repeatedly disassembling vehicles of Tesla and other car companies and assessing the construction from an engineering standpoint. One such firm is Munro & Associates. In 2018, they took a close look at a Tesla Model 3 and came to the conclusion that the rear section of the vehicle had "bad design, too many individual parts, poor manufacturing resulting in wasted profits" (Welch 2018). According to Sandy Munro, CEO of Munro & Associates, Tesla responded to the criticism, changed the whole process, and implemented improvements: "We made recommendations to Tesla and they implemented them very quickly. It doesn't matter whether it's die casting or the octovalve [an important element of the cooling circuit]" (Johanson 2020).

Apparently, Tesla still manages to hold up this cross-functional integration of teams. In 2022, when disassembling the drive unit of the freshly released Model S Plaid, industry expert Sandy Munro found a "far-reaching cross-functional integration". Multiple sub-systems like high-voltage and low- voltage circuits, transmission, cooling, electric motors, converters, and suspension – "they all harmonize in a way that is only possible with cross functional teams." In his own words: "What we are looking at here is a culture that nobody else has, crossing party lines" (Munro & Associates 2022). People from different departments, component areas and crafts are in close connection, implementing quick design iterations, which is reminiscent of the SCRUM metaphor. This can be achieved much faster as if sub-contracted suppliers are involved, especially with the modular control units, outsourced via specification sheets.

Tesla follows a model of "grey innovation" according to Zhang et al., i.e. "an experiment-driven process, often in areas of ambiguity and covering multiple domains". What they state about Foxconn, China's prime manufacturer of Apple products, also applies to Tesla: "Manufacturing is not simply assembly lines connecting together existing modules following pre-specified instructions", it allows "experimentation in production and process innovation" (Zhang, Dodgson, Gann 2022, p. 74).

4.7 Tesla's agile factories

The Factories itself are an example for rapid experimentation. Tesla's first plan in Freemont, California was originally built by General Motors Co. in the 1960s and jointly operated by GM and Toyota until 2009, when it was acquired by Tesla. Since then the plant has seen numerous additions, including tent structures invading the parking lot. In the context of reaching its production goal for the model 3 in 2017, a pop-up assembly line was built in a tent in three weeks, which allowed for additional output in order to reach the 5000 cars per week goal in the production of the Model 3 (The Agile Wire 2021).

Despite that bursting at the seams, by the end of 2021 Tesla's plant in Freemont became the most productive in all of the Americas measured by weekly output of cars. An average of 8,550 cars a week were manufactured, surpassing the 8,427 cars per week at Toyota Motor Corp.'s plant in Georgetown, Kentucky, as well as BMW AG's Spartanburg hub in South Carolina (8,343) or Ford Motor Co.'s iconic truck plant in Dearborn, Michigan (5,564), according to a Bloomberg analysis of production data from more than 70 manufacturing facilities (Randall 2022).

When Tesla proceeded to build its first factory in a greenfield approach, it left behind the legacy of factory design, too, and came up with a diamond-shaped single-edifice plant of huge size, which since then has been the model for all of its factories (Randall 2022). The unique diamond-shaped factory design has since been applied in Shanghai, Grünheide and Austin, Texas. The "Giga factories" are built at great speed: The Shanghai plant took only one year to construct, and two more years to reach a capacity of 500.000 cars a year (Freitag, Rest 2022).

Tesla also sets standards in terms of speed when building the factory in Brandenburg. The Bielefeld based construction specialist Goldbeck was responsible for a large part of the factory in Grünheide. The company executives stated that, although it hadn't been their biggest order in the company's history, it was by far the fastest major order at 100 to 200 million Euros to be executed: "The order came a lot faster than usual. Processes like this, from the idea to completion, take six to seven years in this country with all the permits. But then you have a basically outdated factory. The use of resources increases disproportionately with the size – this is particularly positive in terms of sustainability" (Müller 2022).

5 Conclusion: Towards an Agile Production System?

In the following I will summarize five key findings of this discussion paper and point at further research questions that arise from these.

5.1 A metal-bending digital company

This paper tried to argue that Tesla can be regarded as an example for the entering of digital capitalism's logic into the area of automobile production. When in 2006 Sattelberger, Wempe and Boes described a "future enterprise in the digital society", a "systemically integrated company" characterized by "continuous value-added processes" in which "all functional sub-units are understood as elements of an interdependent system that ultimately aims to create customer benefits" – they seemed to have had Tesla in their minds (Sattelberger 2015, p. 64). Tesla joined the league of digital companies, pushing the societal mode of operation of digital capitalism further into sectors of the economy previously untouched by it. Characteristics of platforms in internet-related and information-heavy areas are distinctly present in Tesla's operations: A software and hardware centered platform model, a corresponding strategy to markets, growth rates and strategies of massive scaling and the perspective on the product as an ever-evolving source of data, fed back into the revenue stream. Therefore, Tesla might best be characterized as a hybrid between an automaker and a digital platform.

5.2 Product and exploitation

Tesla is a digital firm with a digital product targeting a new type of user. Tesla's view on its product is that of a digital device, defined by software and representing an essential element of an electricity and information grid. Over-the-air updates of software and features became central to the user experience. A perpetual beta version is delivered to the customers, with the promise of updates, bug fixes and enhancements in the future, resulting in an ever-evolving product of the kind users are familiar with in the digital sphere. The role of the customer also changes to one familiar to the platform economy. The user experience when buying a car, when updating the device, subscribing and unsubscribing to features such as Full Self Driving – rather resembles Amazon or Netflix.

5.3 Keeping up the pace

According to industry experts, Tesla has a three to seven year technological lead in key areas like batteries, battery management, software, customer relationships, autonomous driving, and digital business models. To maintain this lead, Tesla continues to innovate at a high rate. To this date, Tesla seems to keep up the spirit of constant improvement, questioning industry standards, and heralding first principles. The risky and experimental implementation of new casting technology into current production clearly indicates that. Tesla's technological advantage comes from an organizational model that is built around the developing a software-first product.

5.4 Agility on the shop floor

Tesla is a software company by trade that affronts manufacturing with the methods used in software development. While agile principles conquered the software world by storm in the last two decades, Tesla seems to be a frontrunner in implementing them in manufacturing. Tesla's eagerness to learn as well as its intense prototyping approach makes it reasonable to lean on agile principles. Agile principles found its way onto Tesla's shop floor, facilitated by Tesla's software-development perspective on engineering and manufacturing. Data-driven target definition, self-organizing teams, gathering around issues, problems, and bugs seem to be derived directly from the agility playbook.

The principles outlined in the Agile Manifesto show considerable overlap with aspects of the Toyota Production System (TPS) or Lean Production, like the emphasis on self-responsible groups and continuous improvement. Agile methods originally inherited certain aspects from Lean Production. Principle two of the Agile Manifesto (" welcome changing requirements"), principle four ("business people and developers must work together daily throughout the project"), principle eleven mentioning "self-organizing teams", and principle six highlighting "face-to-face conversation" express similar concerns and approaches as in TPS.

Against the background of Agility being partly informed by methods from Lean Production it might seem far-fetched to expect a re-import into the realm of production of those principles via the Agility paradigm. But the current paradigm is being challenged by increasingly digitally inclined customers and ever- shorter development cycles. The industry struggles to implement design changes quickly. It takes an OEM typically two to three years to implement first designs to production ready. While the Toyota Production System (TPS) made it possible to obtain significant gains in terms of costs, manufacturing times and product quality, for Valentin Tesla marks an inflection point, in which the outlines of a new model.

5.5 A "Tesla Production System"?

Andreas Boes is inclined to affirm the advent of a "new production system after Taylor's and Lean Production" (Boes 2021a), while Valentin speaks of "*Teslisme*" as an "organizational model for the Fourth Industrial Age" (Valentin 2021, p. 57). So are we witnessing a "Fordist moment", a third revolution in car manufacturing – after Fordism and Lean Production – consisting in the migration of software development methods to the shop floor?

While Tesla's efforts to import agile methods to the entire firm can be seen as a paradigm shift within the automotive industry, caution may be advised. Elements of what could be called "agile manufacturing" can be detected, although the evidence for that is limited to certain stages and mostly anecdotal.

Although it might be exaggerated to speak of a distinct "Tesla Production system", indications for a considerable and possibly enduring alteration of Lean Production paradigm can be determined. Agile, which originally inherited certain aspects from Lean Production, comes back to the shop-floor in the context of the software-centred product. As a consequence, the leading industrial paradigm of Lean Production experiences an upgrade and update, informed by twenty years of application of agile methods in the software industry.

In reversing some aspects of the Lean Production paradigm, like liquefying specifications, it rather constitutes an update of a state-of-the-art Lean Production. Above all, it moves away from fixed specifications and towards a continuous integration of product improvements into the very assembly-line production. While parting from the ruling Lean Production paradigm, it builds on a strong vertical integration and a reduced number of products – both reminiscent of Ford's production model.

5.6 Outlook

The following questions arise and demand for further research:

Further analysis of Tesla's operations:

- Can evidence for the application of agility on the shop floor be found in Shanghai, Grünheide, and Austin, Tesla's more recent production sites?
- To what extent is Tesla adapting to local production conditions and engineering traditions, thus altering its playbook in different national and local contexts (Ulrich, Jürgens, Krzywdzinski 2016)?

The significance of agile methods for engineering and manufacturing:

- Is agility deeply and constantly embedded in Tesla's manufacturing or rather limited to certain isolated areas and time periods or phases of production?
- Does Tesla's flirt with agility on the shop-floor constitute a foreshadow of developments all over industry?

Tesla's significance for the future of the automotive industry:

- To what extent does the product itself – the electrically propulsed and software-centered car – steer manufacturers onto a path taken by the frontrunner in the EV industry to become digital firms themselves?
- Are Tesla's modifications in their production system partly a consequence of intrinsic mechanisms of EV production and marketing, in fact not Tesla-specific, and resulting in the entire EV-industry following suit?

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