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The Process-oriented Digital Twin of Construction Machinery

Maximilian Schöberl
Tobias Kalla
Thomas Sauermann
Franz Rimböck
Stephan Kessler
Johannes Fottner

Tobias Kalla
Wacker Neuson SE

Maximilian Schöberl
Technische Universität München
Lehrstuhl für Fördertechnik Materialfluss Logistik

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Rising digitalization efforts in the construction industry come along with buzzwords like the digital twin arising in the discussion about data standards and utilization. In order to foster rigorous digitalization efforts, this paper presents a differentiated taxonomy and related definitions to above mentioned concepts. Leveraging the taxonomy and conceptual frameworks for the implementation of digital twins, machine- and construction-oriented data use cases are outlined. Finally, an industrial case study showcasing a heavy vibratory plate reveals the current state and further developments in the context of process-oriented digital construction machinery twins.

1 Introduction

In the past years, efforts to digitize and digitalize the construction industry gained traction. Multiple initiatives backed by organizations from different industries focus on the development of interoperable and compatible data standards for the description of construction machines [4, 14, 16]. While most of these initiatives use a bottom-up approach, originating from existing data standards implemented on the machines, like the ISO 15143-3:2020 [7], the alleged data use cases are vaguely described through buzzwords like the digital model, shadow or twin. The consequence of the interchangeable and undifferentiated use of these and other buzzwords are ambiguous statements leading to an obstructed discussion of data use cases in the processes, especially of construction companies.
Therefore, this papers objective is threefold. First, the authors propose the assumption of a differentiated taxonomy and related definitions regarding data-related buzzwords in the construction industry. Second, the authors propose a data model to be applied in order to cluster respective data points and introduce machine- and construction-oriented data use cases to the taxonomy, demonstrating its potential. The paper closes with a case study on the conceptual implementation of the taxonomy in an innovation-oriented construction equipment company.

2 Digital Object

To reduce the ambiguous and interchangeable use of buzzwords in the context of digital construction machines, the authors propose a taxonomy introduced by Kritzinger et al., 2018 [8]. In their paper, Kritzinger et al. conduct a thorough literature review on digital twin related terms in manufacturing and come up with a taxonomy for their usage. Generally, they differentiate the terms digital model, shadow and twin by the degree of data integration between the physical object and its digital counterpart. In a digital model, the data flow between the objects is manually. In a digital shadow, the data flow from the physical to the digital object is automated, while there is a manual backflow from the digital to the physical object. In a digital twin, both data flows between the objects are automated. Figure 1 visualizes digital and physical object as well as the data flows for the different concepts.

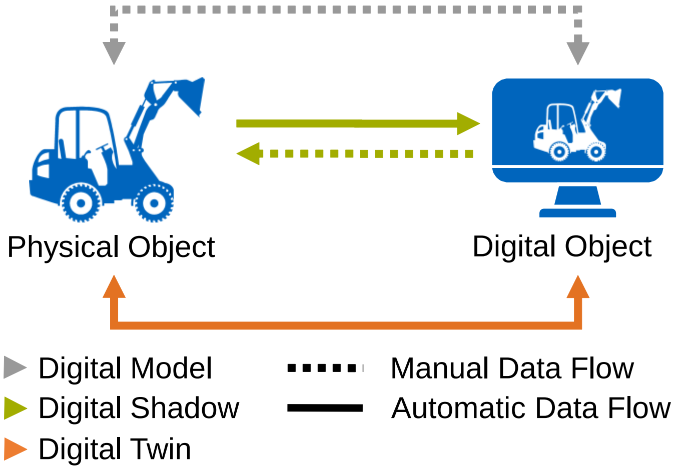

Figure 1: Physical and digital object with digital model, shadow and twin specific data flows.

While the instantiation of the physical object is intuitive, instantiating the digital object is complex but the key to the definition of data use cases. A digital object is usually implemented in form of an application, which processes the data flows. For that, it is reasonable to look into software engineering as creator of applications to acquire an understanding for the digital object concept and its instantiation.

Brügge and Dutoit [3] subdivide the software development process into five activities: requirements elicitation, analysis, system design, object design, implementation and testing. During requirements elicitation, client and developers define the purpose of the system or in this case the digital object, as a description of the system in terms of actors and use cases. Thereby, actors can be end users, other systems and the environment. The underlying challenge in requirements elicitation is that the client and user are domain experts with usually little knowledge in software development, while the developers are experts in software development with little knowledge of the domain and the end user's environment. The same challenge exists in the definition of a digital object. In order to bridge this gap, tools like scenarios and use cases are used in software engineering [3]. This procedure is adopted by other engineering disciplines as well. For example, Wilberg et al. [18] developed a process model for the development of a use phase data strategy to support engineering companies that already offer or plan to offer connected products. In addition, Schweigert-Recksiek et al. [11] present a case-study-motivated procedure model for the introduction of a digital twin, where use cases become the main part of all activities succeeding the project and goal definition. Trauer et al. [12] highlight, that it is not useful to limit the twinning principles to just some specific applications but create a collection of different use cases.

In order to come up with meaningful use cases fixing the information asymmetry between developers and users, it is important to systematically approach the creation of such. Therefore, each stakeholder's viewpoint on the system should be examined and systematically modeled. A viewpoint is a template, pattern, or specification for constructing a view [6]. In addition, according to ISO 42010:2011 [6] a view is a representation of a system from the perspective of related concerns or issues. Figure 2 describes the depicted correlation in a conceptual model.

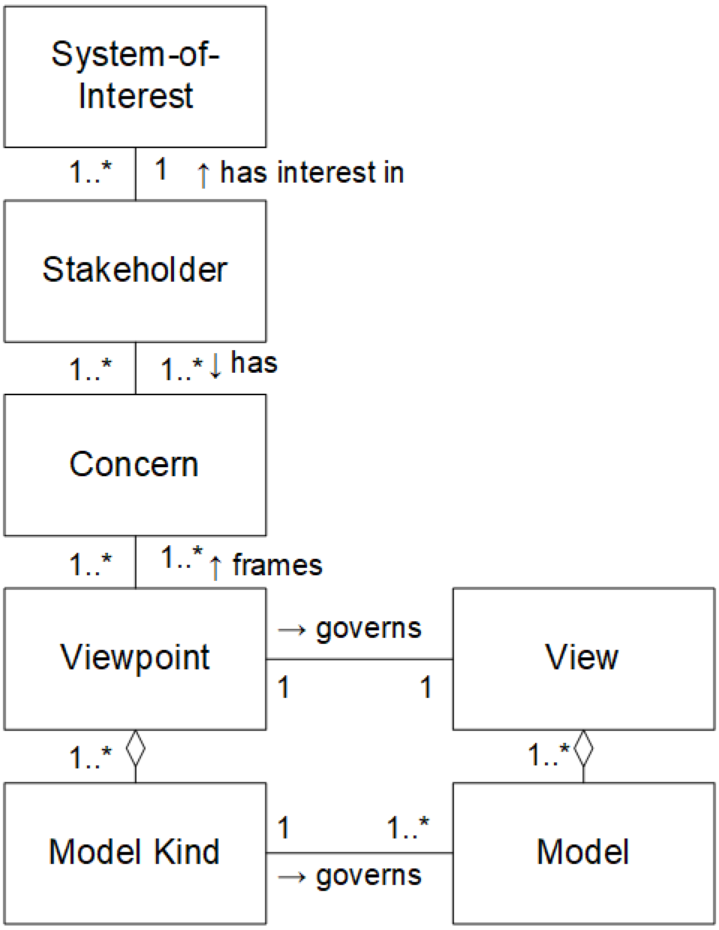

Figure 2: Fraction of the conceptual model presented in ISO 42010:2011 [6].

Regarding construction equipment, a viewpoint on the system-of-interest machine is service. Exemplary concerns of a stakeholder, e.g. service technician, are a minimal effort in maintenance and comprehensible technologies. A view on the system is represented through the maintenance instructions. The instantiation of the view as a brochure represents the model, which is governed by general guidelines for the creation of service manuals, the model kind. As this short example demonstrates, it is necessary to introduce modeling concepts from other industries to the construction industry's debate on data use cases.

3 Data Use Cases

The above defined concept and taxonomy are expected to systematically structure a rigorous use case debate and coordinate standardization efforts. A proposed classification of data points for construction- and machine-oriented users is shown in figure 3. The classes are again classified into the concepts of a digital model, digital shadow and digital twin according to the type of information flow.

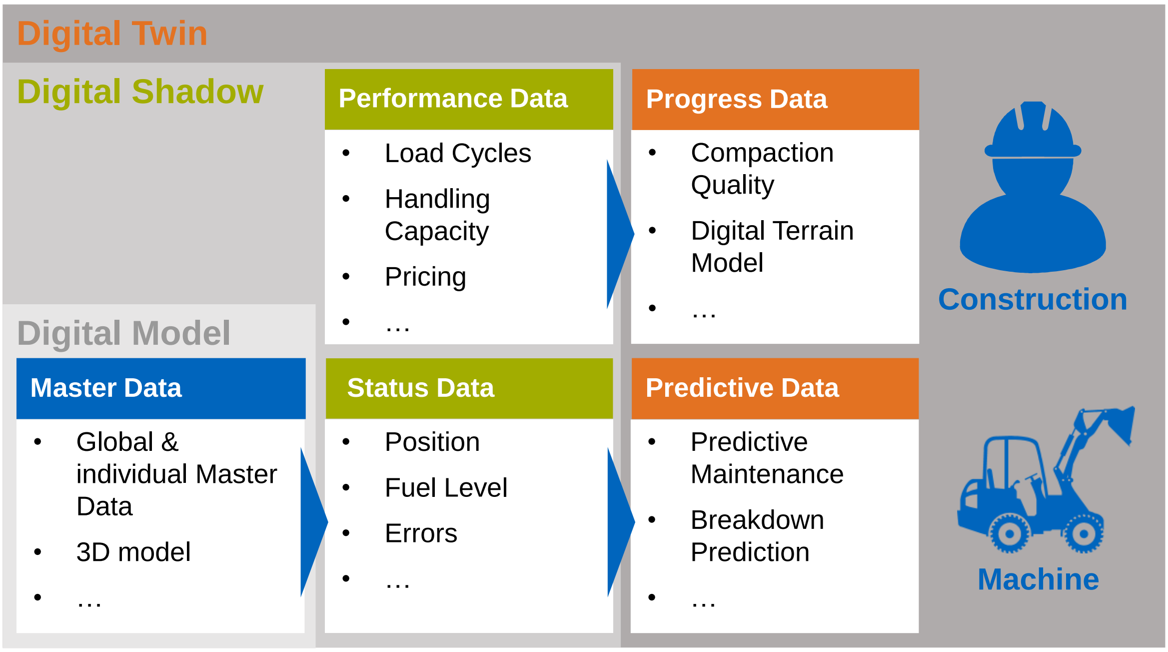

Figure 3: Proposed classification of data points for construction- and machine-oriented users.

Users of the digital object work in different functions at construction companies. Leveraging the taxonomy, the following sections will describe five exemplary use cases for the digital object in machine- and construction-related processes. These are meant to function as guided examples and therefore facilitate the definition of further need-oriented use cases.

The approach to classify those sections within the applied taxonomy is twofold. The authors propose to differentiate between machine and construction site related process data. Therefore, a differentiation regarding the user of the individual clusters is introduced, dividing those use cases in firstly, machine-related processes with a more technical focus and, secondly, planning and progress-oriented sections supporting operational efficiency of construction processes.

3.1 Machine-related Use Cases

For machine-related processes in construction companies, the digital object relies on *master*, *status* and *predictive data*.

Master data follows the concept of a digital model. There are no automated information flows between the objects. The users of master data are equipment engineers and process planners. They are concerned with pre-construction tasks like machine supply and collision avoidance in the transport phase. Exemplary data points are the dimensions of a machine, inventory number or a 3D model. Currently, this data is manually derived from technical specifications and product documents. Organizations, like the VDBUM Zukunftszirkel, are currently working on a digital pipeline to transfer master data between the OEM's and the equipment buying construction company's IT systems [14].

For a machine-oriented digital shadow, *status data* is a vital component. It is state-of-the-art that heavy equipment manufacturers offer telematics solutions to track the position, fuel level and operating status of machines based on the ISO 15143-3:2020 [7]. Fleet managers use this data for a variety of tasks, such as monitoring fleet utilization or the disposition of available machines. Activities of the working group Machines in Construction focus amongst others on the adaption of the ISO norm on construction machines other than earth-moving machines, for which the norm has been created [15].

A machine-oriented digital twin of construction machinery is achieved, if there is an automated, bi-directional flow of data between the construction machine and its digital object. Especially in machine servicing, scenarios like predictive maintenance through *predictive data* prevail for quite a time. A mean to realize this vision is to automatically collect and store machine data, analyze them through algorithmic pattern recognition or KPIs and send maintenance or break down probabilities back to the machine or directly to the service technician. Service personnel is thereby empowered to avoid and plan machine downtimes, as well as systematically choose the machine's end-of-lifetime. As predictions regarding machinery require machine-specific know-how, it is each individual manufacturer's responsibility to drive actions in this field.

3.2 Construction-related Use Cases

Performance and *progress data* support the workflows in construction-related processes.

Automatic surveying of each construction machine's performance creates a vast amount of *performance data* and a digital shadow reflecting operational activities. Bidding and controlling are concerned with quantifying performance by means of cost per output as accurate and fast as possible. Today, standardized KPIs are calculated on the basis of cost catalogues, like the [2, 5], and scarce historic data. In the future, the machine is meant to be aware of its own performance by counting load cycles, payload or other output. On the cost side, a digital shadow improves the accuracy of cost functions, thereby shifting the focus from the machine type to the individual machine. After clarifying the status data standard for each machine type, the working group Machines in Construction 4.0 is currently moving on to the definition of performance data for specific machine types [10].

Closely linked to construction performance data is progress data. *Progress data* follows the form of a digital twin. A digital model is transferred onto the machine, which carries out the work according to the model specifications, compares the current to the target state and finally submits an as-built model. In today's best-case, this workflow is already bi-directionally automated, so that the criteria of the digital twin concept are met. More realistically, this workflow is not fully automated and is of matter in research and precision system company's developments.

The above categorization of current developments and standardization efforts in the presented data categories highlight the taxonomy's potential to systematically structure a rigorous use case debate and coordinate standardization efforts. How the taxonomy can be leveraged to come up with use cases and necessary data is depicted with the help of a heavy vibratory plate in the following section.

4 Case Study: Vibratory Plate

Wacker Neuson's vibratory plate DPU110 gives a perfect example for a physical object going through all the data use cases of the taxonomy. Enabling the customer to achieve maximum value from the construction machine through digital objects tailored to the process-driven needs. Digital objects explained by means of the vibratory plate are (1) a master data template and 3D model for the construction company's ERP systems, (2) status data for service and fleet management, (3) performance data for costing and bidding, (4) predictive data for maintenance and service planning and (5) progress data for project management and quality assurance.

4.1 Master Data (Fundamental Machine Information)

Unambiguous identification of the asset provides the basis for all subsequent application scenarios that build on data generated throughout the machine life cycle. Therefore, an initial synchronization between the physical and the digital asset is inevitable. Usually correlating machine meta information are synchronized with the machine's digital identification number when the telematics gateways are built into the machines in the assembly lines of the production plant. Most information correlates to the machine header information of the ISO 15143-3:2020 [7]. Information like equipment make, model or serial number are standardized and commonly applied across the construction industry. Those data points are synchronized out of the manufacturer's ERP system and used for the identification and filtering logics that can be applied for customer and OEM specific application scenarios in subsequent stages, e.g. for calculating the average fuel consumption for a specific asset class during machine utilization on site. Figure 4 shows a screenshot of equipment master data.

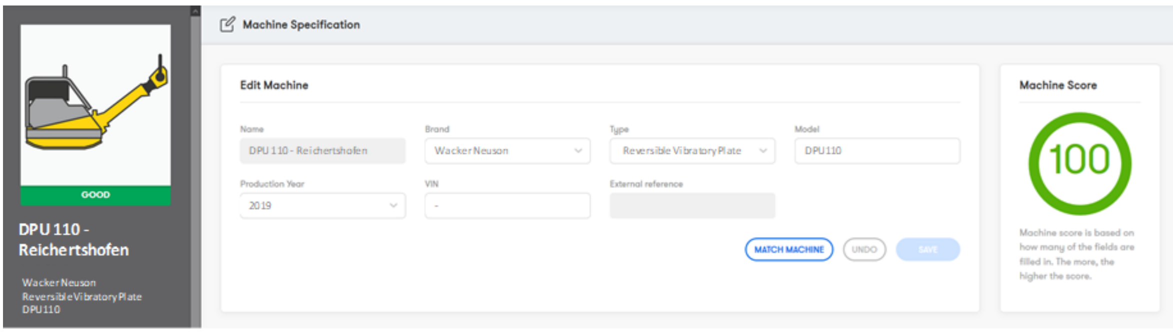

Figure 4: Equipment master data.

Furthermore, we see the trend that machine owners request additional meta information in order to ease end customer processes. The trend of increasing Building Information Modeling (BIM) application rates [1] suggests the extension of machine master data with 3D models that can be integrated into BIM models as well as planning and documentation systems of the customer. Those models can be provided as STEP files in order to check the dimensions of the machines or potential collisions on site to verify the selection of the right equipment for the respective construction sites. Figure 5 demonstrates the visualization of the 3D model of the DPU110 in a virtual reality (VR) environment which creates even further possibilities. The scene exemplarily shows a training sequence for the replacement of the air filter of the vibratory plate.

Figure 5: 3D model of the DPU110 in VR environment.

4.2 Status Data (Service and Fleet Management)

The next stage includes machine status data that. The machine meta information described in section 4.1 is enhanced with additional parameters across the whole fleet. Figure 6 shows the visualization of machine utilization as well as health state parameters which typically used to maximize fleet efficiency. Those parameters are also commonly applied within the construction industry and provide a basic overview of the localization of machines on a map. Equipment that needs further attention (e.g. in terms of a breakdown or due service) is flagged to highlight required actions of a fleet or service manager. Relevant data points are defined in the existing ISO/TS 15143-3:2020 [7] norm which has been revised in 2020.

Figure 6: Fleet management overview.

4.3 Performance Data (Costing and Bidding)

The third stage defines data that describe equipment performance. Data points are within the spectrum of rather unprocessed values like fuel consumption up to values processed on the machine itself (e.g. load cycles) or in the back-end system (e.g. average area performance of compaction). The described data points can all be used for costing and bidding and therefore ensuring the planning of construction sites and projects with equipment suitable for the job to be done. Nowadays, construction equipment lists containing average values are used to calculate utilization and maintenance costs of an equipment during a job on site, but planning accuracy can be significantly improved providing real equipment utilization data from previous projects. Therefore, the mere provision of the above-mentioned data points results in great planning accuracy that can be used during the bidding phase based on data points collected through the experience of past projects. The end customer benefits from the opportunity to base future decisions (e.g. selection of specific vibratory plate to match required compaction performance and area) and offerings on concrete machine data and insights acquired from previous projects and therefore, create superior offers compared to potential competitors.

4.4 Predictive Data (Maintenance and Service Planning)

As of today, service and maintenance planning are done mostly on a manual basis. Service notifications are captured in a machine or service record based on machine type or model or even entered individually into the system for single machines (see figure 7). Automated service notifications are then generated out of most systems, again on an individual basis per asset. Efficiency gains, e.g. levering reductions in preparation and travel times of service technicians are merely realized. In most cases there is no grouping of machines with upcoming due services in proximity to each other or such a grouping is handled on a manual basis including all related administrational efforts.

Date	Name	Client name	Service document	Reference number	Serial number	Hours	Hours service	Hours to next service	Km	Km service	Km to next service
09/02/2020 5:19:51 pm	Weidemann Radlader 1880		Service A - Wacker Neu...	3021070	653210	4.487	5.000	513	2.925	4.000	1.075
09/02/2020 4:46:07 pm	Wacker Neuson Knickgelenkter Radlader WL95		Service A - Wacker Neu...	4055347	609763	3.051	3.000	-51	5.883	5.000	-883
09/02/2020 5:24:06 pm	Kramer Telehandler 2706		Service A - Wacker Neu...	5500020	754620	4	2.000	1.996	98	1.000	903

Figure 7: Service management overview.

Hence, dynamically calculated service intervals bear the potential for huge efficiency gains in daily planning an execution of service and maintenance activities. Building on artificial intelligence (AI) and pattern recognition of an aggregated data base that is fed by real-time machine information across the entire fleet, service related activities can be substantially streamlined. The basis for activities in the field of prediction or even prescription (for distinction between both see Porter and Heppelmann [9]) machine related events like breakdowns or maintenance needs are, again, a heterogeneous data base containing all required information. Equipment status data is necessary to provide e.g. service technicians with relevant information to plan activities even before arriving on a construction site. Descriptive dashboards are used to visualize potential correlations between machine status information and breakdown events and provide trouble shooting insights. This is a crucial step on the way to enable technicians to arrive at data-driven decision-making workflow to support the planning and execution of their daily tasks [13].

Hence, the acquisition of relevant data points on the equipment as well the transmission into a back-end system provide the basis for the implementation of subsequent use cases. The authors see the trend to consistently provide data points also on smaller equipment in order to ease customer and service processes. The following figure shows an excerpt of correlating data points that will be available on future Wacker Neuson vibratory plate generations. Figure 8 shows a simple illustration of the correlation of engine speed with exciter speed as well as oil and engine coolant temperatures. Temperatures increase with equipment runtime duration, where engine coolant temperature is reduced by fan when a critical temperature is reached.

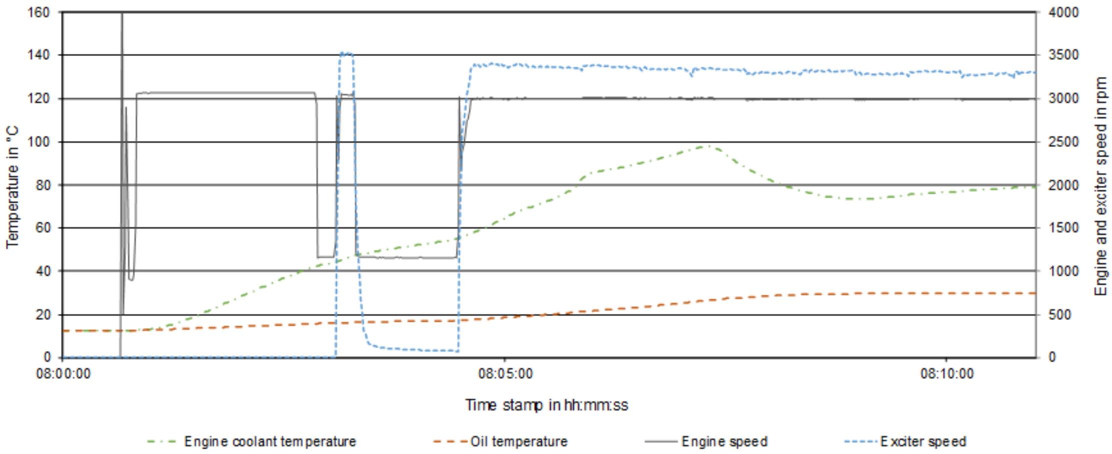

Figure 8: Description of machine data correlations.

4.5 Progress Data (Project Management and Quality Assurance)

The last stage describes machine progress data that are used for project controlling and quality assurance. As of today, processes on a construction site (e.g. planning, project execution or documentation) are executed mostly manually and paper based. The acquisition of progress data provides the basis for increasing downstream process efficiency through the provision of product-related service offerings. Wacker Neuson Compamatic [17] is an example how compaction surveillance on the machine can be combined with data transmission by a telematics module. The solution visualizes compaction quality and progress on site within the telematics platform providing the customer with end-to-end documentation of the compacted area, as shown in figure 9. The result is increased savings in terms of time and cost.

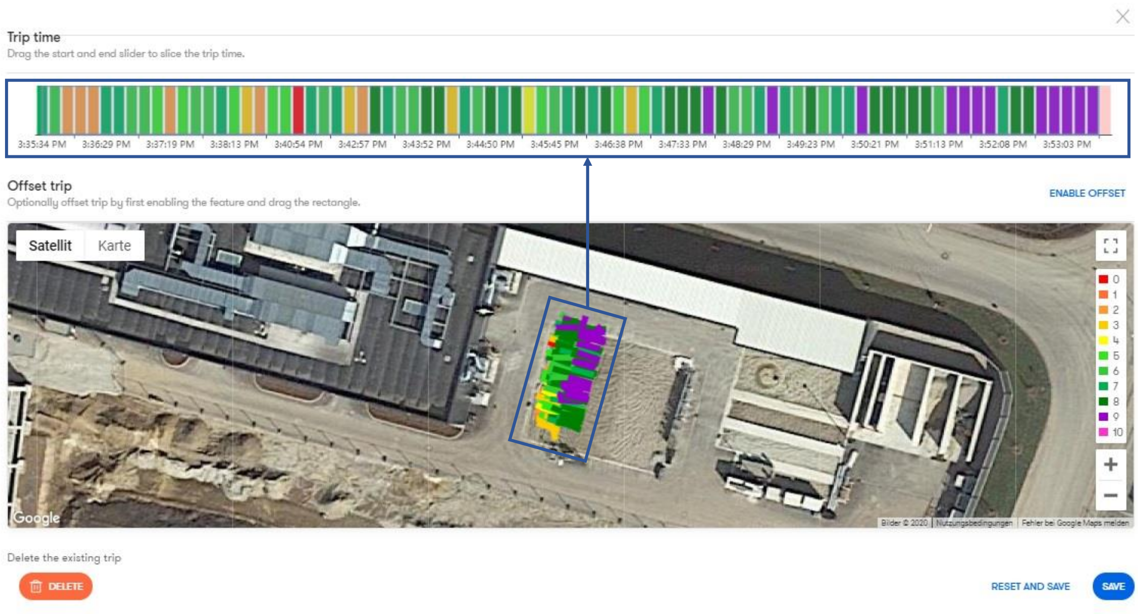

Figure 9: Compaction quality and progress of Wacker Neuson Compamatic in the telematics platform EquipCare.

The concept describes the utilization of the digital objects of an asset with the chosen vibratory plate passing all above defined viewpoints. The case study describes the concept of pairing information between the physical and the digital object. While equipment master data is synchronized via a manual data flow in first instance, the study pursues automated, bi-directional data flows between physical and digital object striving for the implementation of a digital twin.

5 Conclusion and Outlook

Rising digitalization efforts in the construction industry introduce buzzwords like the digital twin. In order to foster rigorous digitalization efforts, this paper presents a differentiated taxonomy and related definitions. Leveraging the taxonomy and conceptual frameworks for the implementation of digital twins, machine- and construction-oriented data use cases are outlined. Finally, an industrial case study showcasing a heavy vibratory plate reveals the current state and further developments in the context of process-oriented digital construction machinery twins.
The main goal of this paper is to present a conceptual framework to facilitate data standardization efforts and furthermore promote digitalization in construction. The outlined use cases are only an exemplary selection of achievable potentials through ongoing

digitalization. Therefore, the authors appeal to equipment managers, equipment manufacturers and construction professionals to actively seek new use cases and realize their potentials. Initiatives like Machines in Construction 4.0 and VDBUM Zukunftszirkel [4, 14, 16] form a great environment by bringing professionals from construction and equipment manufacturing together. The outlined framework and taxonomies are supposed to facilitate interdisciplinary understanding in this context.

In addition to the creation of new use cases, in the near future construction companies will be able to collect a fast amount of data about assets and processes. In order to transform data into insights, it is necessary to start building the required infrastructure today. Through investments into IT infrastructure and data processing capabilities, construction companies will derive future competitive advantages.

Through increased interest in and thereby more economic collection of machine data, original construction equipment manufacturers are able to develop a deeper understanding of their machine's behavior beyond current tests. Data collected during the use phase of the machine will enable manufacturers to tailor their product to the needs of the customers, thereby creating more effective equipment, leading to a better overall performance in construction.

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