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Digital Twins of Operational Scenarios in Mining for Design of Customized Product-Service Systems Solutions

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Abstract

The paper presents an approach, based on the development of digital twins, to support the transition toward electromobility and autonomy in the mining industry, by supporting the design space exploration of future operational scenarios based on different construction equipment and mining site configurations. With such an intent, the paper presents an approach combining systems and systems-of-systems simulations to run trade-off analysis based on different product-service systems (PSS) configurations. Additionally, the paper integrates the "operational context" variables in PSS design simulations to create a digital twin of a "mining operational scenario" customizable for the specific configurations of each mine. The paper exemplifies the proposed approach by contextualizing in a reference mining site describing how the multi-dimensional simulations have enabled PSS trade-off analysis and PSS sensitivity analyses, and how operational context variables are integrated into the digital twin of the operational scenario.

Keywords: Digital Twins; Product-Service Systems; Design, Systems of Systems; Operational scenario, Electromobility, Construction Equipment

1. Introduction

In recent years, digitization, electrification, and autonomous systems have enabled increases in productivity and efficiency in nearly all industrial applications. Construction equipment manufacturers have presented their first fully electrical machines integrating different levels of autonomy, aiming for a zero-emission and zero accident future in the construction industry [1]–[3]. The new scenario will drastically reduce air pollutants, increase workers' safety, and reduce the cost of operations. However, while the possibility to drive fully electrically and autonomously on a single machine is nowadays a reality, there is still a low understanding of the implications of scaling this innovation up to a network of machines. Such collaboratively integrated systems are termed as "system-of-systems" (SoS) [4]. A mining environment typically comprises of such SoS working in symbiosis with infrastructural elements, such as crushers, service buildings, charging stations (when electric vehicles are included), communication hub, etc., under a dynamically changing environment. A lot of uncertainties exist about how the SoS will behave in such an operational scenario featuring services, infrastructure, and changing operational contexts. Engineers face the challenge of understanding what productivity will be granted, which costs will be generated, and ultimately, what value will be created by electrified and autonomous systems in comparison with conventional human-driven operations at mining sites. Additionally, the transition toward electrical machines opens the possibility for engineering designers to rethink the overall product platform of the major construction machinery and mining machinery equipment, challenging established product requirements for what concern, for instance, weight, capacity, uptime, and dimensioning. From a mechanical engineering standpoint, engineering designers can benefit from a simplified

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product architecture granted by electrical engines (i.e., a general reduction of numbers of components and subsystems needed), from an operational scenario perspective they also need to deal with an increased number of service-related and systems-related design challenges to be analyzed and eventually quantified in the early stage of design. At the same time, while well-validated simulation approaches for product performances exist (e.g., stress analysis, fluid dynamics, modal analysis) [5], the same cannot be said for the level of maturity reached by simulation methods addressing the challenge of quantifying service and systems-related aspects. Research literature commonly refers to such a shift in engineering focus as a transition toward Product-Service Systems (PSS) design [6]. Building on such a gap, the paper aims to present an approach that allows 1) the combination of system and SoS simulations to run trade-off analysis based on different PSS configurations, and 2) the integration of the PSS along with the operational context into a digital twin (DT) to simulate various operational strategies of the PSS under the influence of the contextual variables. The intent is to enable the manufacturing industries to leverage the use of DT in their early design phase to make decisions on both, PSS configuration and operational strategy, ultimately enabling an estimation of the effect of the transition toward electromobility and autonomy of construction equipment in terms of optimal performance, productivity, cost, and environmental impact.

The paper exemplifies the approach by contextualizing it in a reference mining site describing how the multi-dimensional simulations have enabled PSS trade-off analysis and PSS sensitivity analyses, and how operational context variables are integrated into the digital twin of the operational scenario.

2. Research approach

The research has been performed in the frame of participatory action research [7] that enabled the close collaboration between practitioners and researchers and granted access to sensitive information that would not have been possible to access otherwise. The data collection phase and the problem definition activities have been run in collaboration between the academic institution and a major company operating in the field of construction equipment. The existing literature in the field of systems engineering and PSS design was studied to identify strengths, weaknesses, and similarities of the currently available approaches for the development of the DT. Literature in the field of vehicle dynamics for electromobility was combined by data collection about available battery technologies and performances. Transcriptions and notes from interviews, internal conferences, and formal and informal discussions were used to identify the industrial needs and have driven the definition of the reference mining site used as an example. The initial dataset made available by the partner company has been modified and complemented with realistic data and contextualized in a fictitious mining scenario. This was done to avoid the exposure of sensitive information, however, they conserve a reasonable degree of credibility to assure a realistic description of the results. Product and systems simulations have been run using commercially available software.

3. An approach to developing digital twins supporting electromobility transition in the mining industry

3.1. The need for a digital twin in the design of electrical and autonomous vehicles in the mining industry

The design and the features of fossil-fuel-based construction machinery for mining are well established for decades and are based on product platforms showing little variation in the overall product architecture [8]. This is reflected also in many of the first prototypes of electrical and autonomous machines presented by major constructors worldwide which mainly consist in the integration of the electrical and autonomous layer in the established machine platform [8]. However, going beyond the first prototypes demonstrating the technological capabilities, the need to make the transition toward autonomy and electromobility profitable push for the re-design of a whole ecosystem of products and services.

DTs are increasingly developed and used to integrate multidimensional simulation and support decision-making in complex situations [9]. While a majority of the applications of DT are in the manufacturing/production-related [10], one can lately find applications of DT in the realm of products [11], services [12], and product-service ecosystems [13]. DT also seems to facilitate multidisciplinary and heterogeneous simulations of complex systems, especially enabled by the building block correspondence of Model-based Systems Engineering [14] [15]. Anchoring the inferences from these studies, one trend was clear that the DT embraced a high-fidelity representation of the physical space. Such an approach may not be suitable for early-stage decision-making that is typically subjected to many uncertainties. Thus, the empirical study primarily focused on the collection of needs and expectations for the use of DTs in the early stages. More specifically, the focus was to utilize DT to enhance the design space exploration, allowing preliminary design analysis from the subsystem level (e.g., vehicle components, such as battery and engine, to the system level (i.e., the electrical vehicle), to the SoS level (i.e. the fleet of vehicles), to the PSS level (comprising of the SoS, the associated services, and the mining infrastructure), and finally to the operational scenario level (i.e. including the simulation of different operational context).

From the analysis of the qualitative data collected during the participatory action research, four requirements emerged as highly relevant to be granted by a digital twin of an operational scenario in the early phases of design:

- The DT shall make operational scenario-based simulations for alternative requirements (such as site productivity, operational costs, emission footprint, etc.) available in a matter of minutes to have them available during pre-defined decision meetings.
- The DT shall establish all the hierarchical links, right from the subsystem level to the PSS level, allowing the decision-makers to forecast the impact of change at any level in the hierarchy.
- The DT shall increase the awareness of uncertainties and secondary effects linked to the transition to electromobility

and autonomy concerning both economic and environmental aspects.
- The DT shall create a set of generic replicable approaches to simulate the transition towards electromobility and autonomy for subsequent operational scenarios.

Such four requirements led to the development of the DT solution presented in the following sub-sections. An electrical hauler has been selected as the reference vehicle to demonstrate the DT-based approach. A hauler is a construction equipment, typically used for transporting material from one point to another in a mining site. It is used in mining in a variety of sizes and power based on the type, dimensions, and quantity of material that needs to be transported, leading often to the commercial differentiation as an articulated hauler or heavy hauler. The choice of a hauler as a reference product was given by the high impact on emissions in a mining site, by the relatively simple and repetitive tasks, and, nonetheless, for being one of the first construction equipment that has seen the presentation of a fully electric version on the market by major manufacturer worldwide.

3.2. Combining vehicle and site simulations into the digital twin of the operational scenario.

The DT of the operational scenario presented in the paper consists of two interlinked platforms, the “system platform” and the “scenario platform”. The system platform has its roots in Model-based Systems Engineering and in the integration of various disciplines such as mechanical, electrical, electronics, software, etc. [16] to allow the simulation of the effect of different system configurations and control strategies and systems level. The scenario platform has its roots in Discrete Event Simulation (DES), which evolves by a predefined advancing mechanism and state changes are allowed only at separate points in time [17]. The scenario platform represents the SoS, associated services, and the influencing contexts collectively.

The logic of the developed DT can be described as a five-step process visualized in Fig. 1 and described as follows:
- At the subsystem level, the model-based depiction of the system (i.e., the vehicle) in an integrated architecture allows design space exploration of various system configurations.
- At the system level, different configurations of the vehicle allow performance benchmarking using various control strategies.
- At the SoS level, each system (i.e., vehicle) with its respective configurations and control strategies collectively evolve a characteristic behavior of the SoS.
- At the operational scenario level, the SoS behaviors, service strategies, and infrastructural capabilities (i.e., the PSS) achieve a certain degree of value fulfillment under the influencing contextual variables.
- Based on the desired degree of value fulfillment, the requirements are propagated hierarchically from the PSS to subsystem, and the cycle is iterated.

The development and deployment of the DT in the reference case consisted of the combination of these system and scenario simulations at different levels of granularity that provide input and output to each other, respectively. Fig. 1 shows the logical structure of the DT comprising of the system and scenario simulation models connected hierarchically. The system simulation (i.e., the vehicle) is analyzed for various configuration and control strategies via mathematical optimization such as linear, quadratic, stochastic, and/or dynamic programming, and/or heuristics or a combination of these methods. The scenario simulation (i.e., the mining site) evolves over time via DES for a predefined time window using the system configuration and control strategies. The details of the interaction between the models are shown in the IDEF0 diagram in Fig. 2. The operational scenario inherits the contextual variables such as topology, ambient temperature, ore properties, etc. At the PSS level, the decisions mainly relate to the location of extraction points, path planning, battery charging facilities, etc. under these contextual variables. The SoS comprised of several vehicles integrated into a network to achieve the desired ore production. At the system level, the payload, mileage, and power drive configuration of the vehicle, eventually guide the decisions at the subsystem level such as battery capacity, motor power, transmission system, etc.

The demonstrative case features the development of simulation models for every electrical hauler moving in the mining site, encompassing, for instance, vehicle dynamics, motor, transmission, and battery models. All of those are influenced by the gradient of the path that the vehicle will need to follow in the inferred mine. The gradient model is defined for each vehicle following a different path, and it is a function of the topography and configuration of the mine obtained from the operational context data of the mining site. In parallel, the mining site is geo-localized, allowing the gathering of data about site dimensioning and topography. Based on such information, the DT of the operational scenario is created by establishing the position of the extraction points, of the processing stations (e.g., crushers, stockpiling), and the supporting infrastructure (e.g., battery charging station). The DES environment allows the integration of GPS maps for the geo-localization of the sites. Additionally, it allows the definition of alternative paths to be followed by the electrical hauler as well as the possibility to manually interact with the visualized models by “drag-and-dropping” relevant processes (i.e., crushers, charging stations, extraction points) to different locations to test alternative mine configuration and re-run the simulations in a matter of minutes. The behavior of the haulers in the DT is driven by the system simulation giving optimal speed, payload, battery capacity, battery charging, and discharging time (the details of these interactions in the DT are presented in section 3.3).

3.3. Input, output, controls, and mechanisms of the DT in the reference scenario example

The example presented is based on a vehicle simulation model created in Matlab and a Site Simulation model created in a Discrete Event Simulation environment, those which communicate between each other via a data spreadsheet table.

For communication purposes an IDEF0 notation is used in Fig. 2 to visualize how data are shared in the proposed approach highlighting input, output, control, and mechanism.

The **vehicle simulation** relies on mathematical optimization and the input to the vehicle simulation is the specification of the vehicle platform along with the architecture, and the technological constraints. Several control options are modeled to reflect the need to simulate the electromobility scenario. In detail, requirements about the vehicle speed in a mining context are introduced (i.e., an upper boundary and a lower boundary for what concerns the vehicle speed). The type of scenario under consideration, i.e., full electric, full diesel, or a hybrid of both electric and diesel-driven machines, sets the need for the selection of different types of engine and efficiency models in the vehicle simulation. Data on the map topography are used to create the gradient model for the paths followed by the vehicles, and the path themselves are defined out of the mining site map including the extraction points, charging stations, and the positioning of the different processes needed in the mine.

In this case, the map of the site was obtained using satellite pictures and its topography extracted from the GPS coordinate from Google Earth. The topographical data (e.g., the distance between objects, altitude) were imported into a computational software (MATLAB® in this case) and were used to define the gradient model for each vehicle path. It must be noted that, for a design choice, each vehicle was assigned to serve a unique extraction point, thus each vehicle followed a specific pre-defined path. In other words, multiple vehicles could serve "extraction point 1", they all followed the same path and sequence of starts and stops, and they will not be able to change their path to serve "extraction point 2" during the simulation. This choice was made both to be able to optimize the configuration of electrical haulers for each extraction point in terms of time (a strong driver for productivity) and cost; and, to initially integrate the logic of programming the movement of the hauler as of an autonomous driver-less vehicle following a predefined working path. The output from the mathematical optimization is obtained in the form of a Pareto front based on the time vs cost of alternative design configurations and control strategies of the haulers. Each point of the Pareto front corresponds to a specific combination of configuration and control strategies for the hauler providing parameters such as vehicle payload, battery capacity, velocity profiles, discharging rate of the battery along the vehicle path, and charging time for the battery at the charging stations. All these parameters, for each optimal point of the Pareto front, are used as input for the site simulation.

The **site simulation** takes as input the aforementioned parameters and relies on DES to evaluate the performance of the site along a defined lifetime. The operational scenario is defined by the integration of a GPS-derived map of the site with the manual inclusion of the location of extraction points, charging stations, and crushers. The site productivity requirements are inserted as a control option as well as the desired scenario choice (only electrical vehicle, only diesel vehicle, or combined presence of both). Additional service constraints can be added as input depending on the specific site configuration or material. In detail, the simulation is composed by events, defined as the processing stage that the material follows in the site, entities, defined as the material that moves from the extraction points to the departure from the site, and by vehicles that extract, load, unload and transport the material around the site. All the entities (such as the vehicles, processing stations, charging stations, maintenance stations, etc.) and their collaborating function as "events" within the operational scenario, and they have their own attributes that are either imported from other simulation models (such as system simulation) or user-defined within the DES environment, (SImulation Modeling framework based on Intelligent Objects – Simio®, in this case). This allows the results to be used for PSS design trade-off to verify 1) the feasibility of a specific site design based on the type of vehicle desired and given the productivity constraints of the customers; 2) the emissions produced by the site in terms of CO_2 and other pollutants given

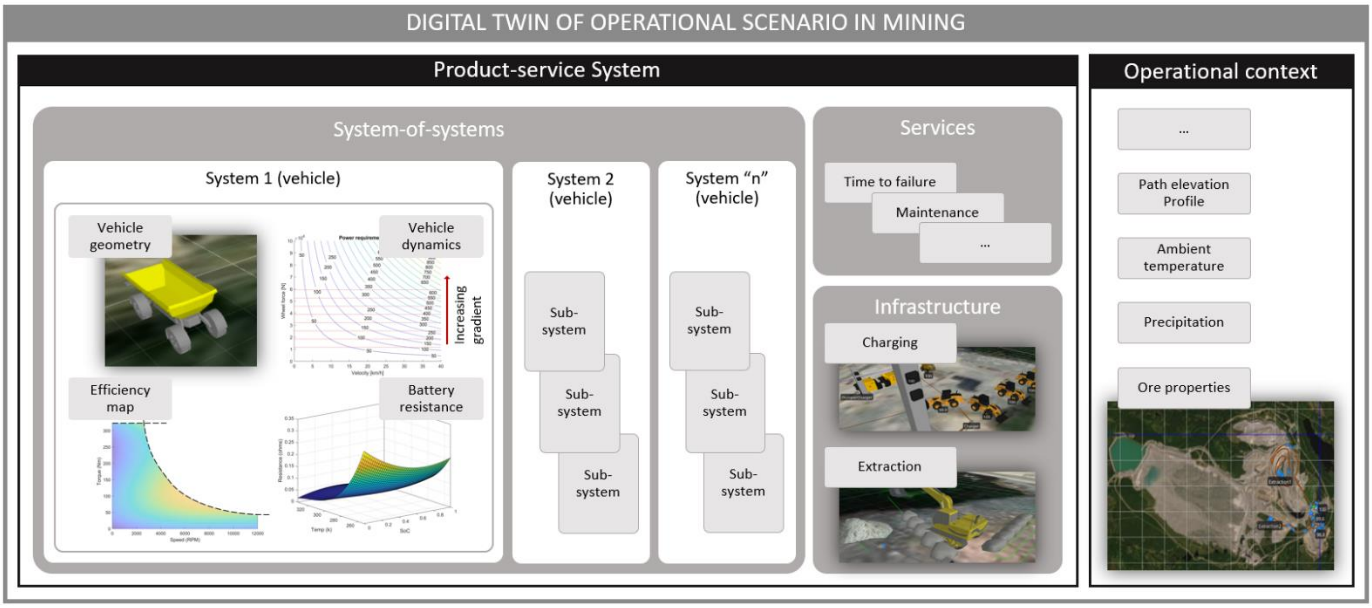

Figure 1: The hierarchical structure of the digital twin of the operational scenario in mining combines systems of systems simulation with services and infrastructure into PSS simulation and ultimately integrates operational context variables.

different site configurations; 3) the simulation of specific site effectivity key performance indicators such as the vehicles uptime, idle time, or the vehicle costs. Additionally, every attribute and variable in the simulation (both at vehicle and site level) can be manually overridden to allow analysis for future scenario simulations. This enables the possibility to run quick what-if analysis both at vehicle level and at site configuration level (for instance the effectiveness of different site layout could be simulated drag and dropping crushers, extractions points, charging points, or other site facilities in other locations in the GPS map in the DES environment).

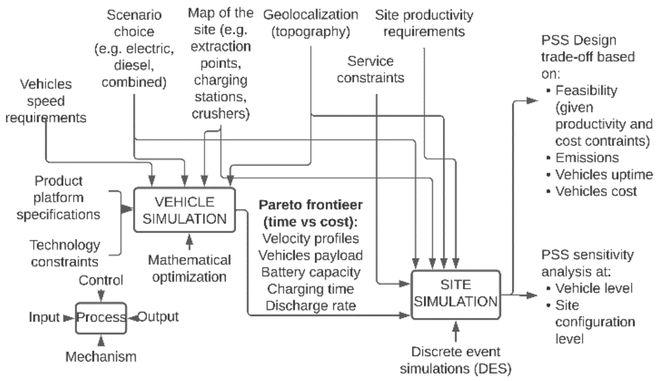

Figure 2: IDEF0 representation of the proposed approach highlighting processes with input, controls, mechanisms, and output.

3.4. Examples of results

This section provides an example of the implementation of the approach in a fictitious mining scenario featuring 2 extraction points, one charging point for electric vehicles, a first crusher, a second crusher, a stockpiling station, and a departure station. To grant industrial secrecy all the shown data shall be considered fictitious. The example focuses on the development of an electric hauler with battery capacity and payload optimized concerning production time and cost relying on the inputs presented in section 3.3. Fig. 3 shows an example of the visualization of the Pareto curve for the design of an electric hauler serving one of the extraction points. Here, 13 different Pareto optimal designs, obtained by the system simulation, are clustered based on battery capacity and vehicle payload. As shown in the upper right corner of Fig. 3, each optimal point corresponds to an optimal velocity profile for the vehicle including the different stops in the site (green line when the vehicle is unloaded and orange line when it is loaded). The velocity profile is related to the altitude and the gradient variation of the path followed by the hauler (black line with grey shadow). Finally, the figure shows the variation of the battery state of charge along the path (blue line). In the case in the figure, the extraction point is located at a higher altitude compared to the other processes, thus allowing the battery to be consistently recharged when the hauler is driving downhill fully loaded.

Fig. 4 Shows a snapshot of the DES environment where extraction points, charging stations, stockpiling, and crushers are modeled as a process in the DES. Additionally, the figure shows the altitude variation of the path to be followed to perform a work cycle on the two different extraction points. In

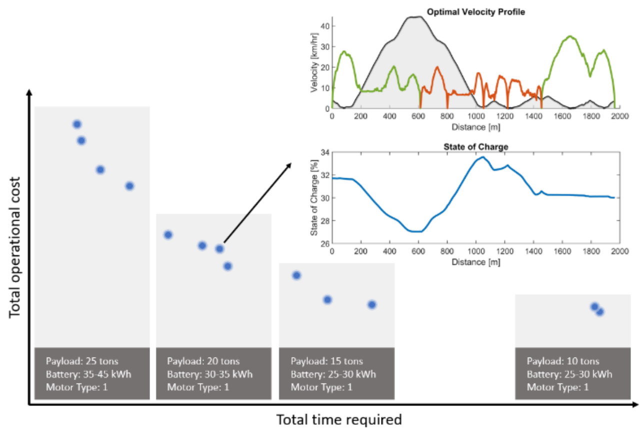

Figure 3: Example of results from vehicle simulations. 13 optimization points are clustered long the Pareto frontier. The top right graph shows a detail of the data related to each of the optimal points

the DES environment, alternative design parameters for both the vehicle and the site can be inputted to simulate the final performances in terms of production, operating cost, schedule utilization, etc. In particular, in the bottom part of Fig. 4, three simulation experiments are visualized for a fully diesel-driven site, a fully electrical site, and a combined site working with both electric and diesel machine.

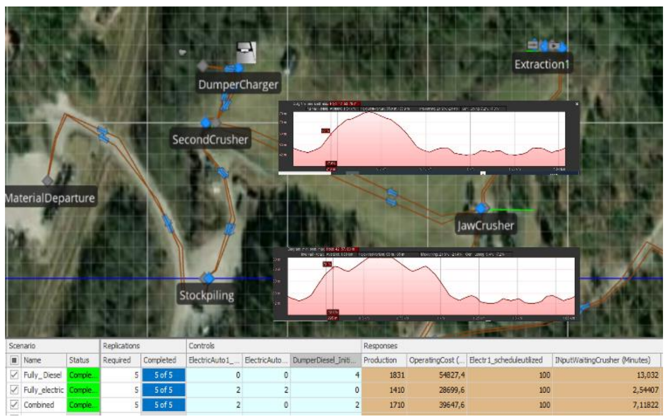

Figure 4: Screenshot from the DES environment including altitude profiles for the vehicle paths and examples of results of the simulations featuring diesel driven, fully electrical, and hybrid vehicle scenarios (bottom rows)

4. Discussion and conclusions

The paper has described an approach to develop digital twins supporting electromobility transition in the mining industry and has exemplified it on a fictitious mining scenario. The digital twin of the operational scenario presented in the paper is meant to be able to drive the development of customized PSS solutions in the mining industry now facing the transition toward electromobility and autonomy. To understand the profitability and the utility of such solutions there is a primary need of ensuring a physical-to-virtual (P2V) connection between the state of an existing physical and digital object. In other words, the state of the physical entity (i.e. the operational scenario as defined in the paper) is captured and utilized to update the virtual entity accordingly. Limiting the data exchange to a P2V connection is referred to in literature as a Digital Shadow [18]. What the approach seeks to achieve is however a DT solution including a virtual-to-physical (V2P) connection, where the simulation run in the digital object can trigger a state change in the physical counterpart (i.e. the operational scenario). Although the approach presented being developed to enable a DT, the current state of the practice in the mining industry example do not yet feature the existence of fully electrical and autonomous operational scenarios from where the P2V data could be obtained, rather the creation of a pilot of such environment shall be seen as a future step of the presented work.

The work can be theoretically positioned at the boundaries between Model-Based Systems Engineering and DES for PSS design. The adoption of the approach will allow engineers designing fully electrical and autonomous machines to integrate into an interactive simulation environment the vehicle, the process, the environment, and contextual factors allowing for the future scenario testing of new systems with new machine concepts in the realm of PSS. This will allow to quickly forecast, in an early stage of development, the economic and environmental impacts of new machines and systems configurations. This capability is expected to consistently reduce the development time and the time to market for cost-efficient autonomous solutions based on electromobility in the construction equipment, speeding up the shift to a fossil-free industry, while, at the same time, lowering the environmental impact and delivering a safer workspace by moving away workers from risky environment. Additionally, the work is expected to generate industrial benefits in terms of:

- Generating consistent savings in development costs and reducing the risk for late design modifications.
- Gain competitive leadership advantages for the delivery of fully electric and autonomous sites.
- Being capable of quickly reacting to new legislation prescribing the measurement and emission of air pollutants in quarries and mines.
- Being capable of quickly running cost and revenue feasibility analysis of new machines or systems configurations by trading-off their reduction of the environmental impact.

The problem identification, the requirements definition, and the investigation of the rationale and logic of the presented approach have been performed in collaboration with a single company, thus those can be subjected to the traditional biases of single case analysis. Further development of the approach is currently testing the approach in different industrial settings to validate and generalize the findings in other industrial contexts.

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