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UTILIZATION OF VIRTUAL COMMISSIONING FOR SIMULATION-BASED ENERGY MODELING AND DIMENSIONING OF DC-BASED PRODUCTION SYSTEMS

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ABSTRACT

The transition toward DC-based industrial grids demands accurate yet efficient planning methods. This paper presents a simulation-driven approach that integrates existing virtual commissioning (VC) models to estimate power demand in early design stages. A minimal-parameter modeling technique is proposed to extract dynamic load profiles from 3D multibody simulations, which are then used for electrical component sizing and system optimization. The methodology is validated using a demonstrator setup consisting of a lift tower and a six-axis industrial robot, both tested under AC and DC operation. Simulation results show close agreement with real measurements, highlighting the method's ability to capture realistic load behavior with low modeling effort. The approach offers seamless integration into existing planning workflows and supports dimensioning of safe, efficient, and regulation-compliant DC production systems. This contributes to reducing component oversizing, improving energy efficiency, and accelerating the adoption of DC grid architectures in industrial environments.

1 INTRODUCTION

The "War of Currents" was a dispute for the standardization of the electrical power grid at the end of the 19th century between the proponents of alternating current (AC), George Westinghouse and Nikola Tesla, and the proponent of direct current (DC), Thomas Edison. This historical dispute laid the foundation for the modern AC power grid, as it allowed for more efficient transmission of electrical energy over long distances due to the efficient high voltage transformation with transformers (Kundur 1994).

However, the advent of modern power electronics has changed the situation. Numerous devices, in both domestic and industrial contexts, function on DC or, at the least, employ DC intermediary circuits. This has led to a persistent need for the conversion of AC to DC, a process that is energy-intensive and has a negative impact on overall energy efficiency (Dragicevic et al. 2016).

The introduction of industrial DC grids can significantly reduce and optimize these conversion stages. Initial DC reference systems have demonstrated potential energy savings of around 12 %. Beyond efficiency, DC grid architectures, typically requiring only two to three current-carrying conductors compared to three to five in conventional AC systems, offer substantial material savings, with copper usage potentially reduced by up to 40 %. Moreover, energy storage systems and renewable energy sources are easier to integrate, enhancing energy self-sufficiency and contributing to the reduction of CO_2 emissions (Savage et al. 2010; Sauer 2021).

The most prominent DC-based factory in Germany to date is Schaltbau's NeXt Factory, where DC is already being used on a larger scale for warehouses and renewable energy supply. This initiative has yielded notable outcomes, including a 15 % enhancement in energy efficiency, a 35 % reduction in annual energy costs, and an 85 % decrease in peak loads through the utilization of recuperation energy (Krause 2023). In addition, industrial DC grids are currently being developed in Forbach (France) with the company Lapp, as well as in Blomberg (Germany) with Phoenix Contact.

Despite these benefits, the widespread adoption of industrial DC grids faces several barriers. The expertise required to systematically design such systems remains limited to a small group of specialists. Many essential components are still in prototype stages, and knowledge about their properties and application remains scarce. Furthermore, critical components such as energy converters and protection devices are often significantly oversized, not only due to a lack of comprehensive system understanding but also due to the absence of known load profiles, which necessitates substantial safety margins during system design. This results in excessive costs and limits economically viable grid planning, as converters and components operate in inefficient operating points.

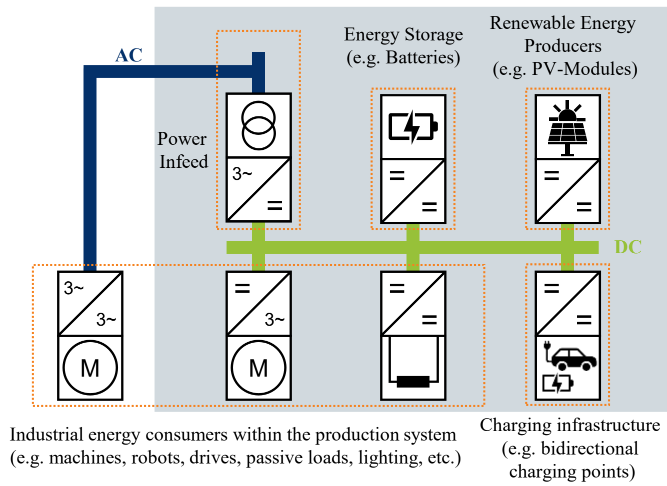

Figure 1: Industrial hybrid AC/DC grid with exemplary generic grid participants (Barth et al. 2024).

The aim of this contribution is to develop an approach that considers the energetic behavior of industrial DC grids during the planning of production systems Building upon existing 3D simulations, which are typically used in virtual commissioning (VC), a minimal-parameter-based method is proposed to systematically capture the energy behavior. Based on this, simulation-driven selection and optimization of appropriate components can be conducted, laying the groundwork for economically and energetically efficient grid design.

The structure of this contribution is as follows: After providing an overview of the current state of research in simulation-based energy planning methods, the developed structured methodology is introduced. This is followed by validation and discussion through an application example based on a demonstrator.

2 STATE OF THE ART

The simulation of energy-related factors in production has already been the subject of numerous studies. Mawson and Hughes, describe various simulation options and approaches in their publication on increasing the energy efficiency of production systems. In particular, they address the coupling between production systems and technical building equipment. In their approaches, production systems are typically modeled using discrete-event simulation (Mawson und Hughes 2019).

In Garwood et al. (2018) various simulation paradigms that address the simulation of energetic behavior in the context of manufacturing are reviewed. In particular, the paper addresses the coupling between Building Energy Modelling and the simulation of manufacturing processes. Here simulation frameworks and tools are presented and compared according their consideration in the factory.

Roemer und Strassburger (2016) summarize the state of the art in the field of energy management, focusing on the intersection of modeling, simulation, and operations research.

Russwurm, in her dissertation on the combined material and energy flow simulation of automated production systems, presents a co-simulation methodology that integrates various engineering tools, particularly for cost-effective storage design (Russwurm 2024).

Paryanto et al. focus on the energy simulation of robots using detailed dynamic systems simulation to optimize and reduce energy consumption, with a comprehensive analysis of various factors influencing loss calculation in robotic systems (Paryanto et al. 2015).

A current state-of-the-art review of the influencing factors in energy-related discrete event simulation is published by the ASIM and presented in Wenzel et al. (2024) through various application cases.

In a previous publication, various modeling paradigms for the energy simulation of production systems were examined in detail and structured into a taxonomy in Barth et al. (2023). This taxonomy provides a structured classification of various simulation techniques used to determine the energy behavior of process participants—based on their modeling and application levels within a hierarchical structure of production systems, different modeling approaches such as empirical load profiles, data-driven methods, analytical equations, state-based, and numerical methods, and the underlying simulation types, including discrete-event, agent-based, or continuous simulations.

According to Thiede (2012), the simulation of energy flows in production systems can generally be divided into three distinct paradigms of simulation architectures:

- A) Modeling and simulating the production system in an application for process simulation (e.g., Plant Simulation). The consideration of energy influences of the process takes place in a separate evaluation tool.
- B) Coupling different simulation domains e.g. through co-simulation to consider dynamic properties of energy flows.
- C) Monolithic integration of energetic influences into the simulation application of the process domain.

These existing approaches primarily address energetic influences in production planning and operation. High-level methods, such as state-based methods in discrete event simulations, lack the temporal dynamics and bidirectional energy flow characteristics needed to plan and evaluate DC grid behavior.
On the other hand, detailed physics-based models offer higher accuracy but require substantial modeling effort and domain expertise, limiting their use in early-stage planning.

Therefore, a clear research gap exists for simple yet dynamically accurate simulation methods that can capture the energetic behavior of DC-based production systems with minimal parameterization. Such a method would empower planners to realistically estimate load profiles, avoid component oversizing, and accelerate the adoption of DC grid architectures in manufacturing environments.

3 METHODOLOGY

The proposed methodological approach builds upon the VDI Guideline 3633 (VDI 2014), which outlines a structured procedure for simulation studies in production and logistics systems and the concept introduced in a previous publication (Barth et al. 2024) in which a software architecture was developed for the planning of industrial hybrid AC/DC grids. A central element of this approach is the unidirectional simulation coupling between the process domain, which represents the energetic behavior of individual system participants, and the electrical grid domain. This involves the paradigm B of energy flow simulation in production systems according to chapter 2.2. In this approach first, the energy behavior of the individual components, such as consumption and generation from sources like PV, is determined. Next, the resulting load profiles are transferred to a prosumer model, which is used as input in the electrical grid simulation. The load behavior is determined using various methods, such as measured load profiles, discrete-event simulations, or, as presented in this work, existing 3D simulation models with embedded physics engines, commonly used in the VC of production systems.

A key advantage of the approach building upon 3D Models is its seamless integration into existing industrial planning processes. In numerous companies, VC with 3D simulation models (e.g., Siemens NX MCD, iPhysics, or ISG-Virtuos) has already become an integral component of the engineering workflow. These environments are utilized for the purposes of testing control code, validating process sequences, and detecting collisions in an early stage. The methodology presented here enhances this framework by introducing an energetic component. Relevant dynamic parameters are extracted from the 3D simulation and transferred to an energy model that enables the calculation of power behavior of a component.

The use of this unidirectional simulation coupling between the process and electrical domains is justified by their limited interdependence. According to VDI 4465 (VDI 2021), separate models are appropriate when significant coupling is absent or sub-objectives can be addressed independently. In this case, energy profiles generated in the process domain serve as input for the electrical grid simulation, enabling realistic load modeling. In this context, interactions of the electrical grid with the production system, such as potential power outages, are not considered in the process domain. However, these effects can be adequately addressed through the grid simulations, particularly in the context of system planning and component sizing.

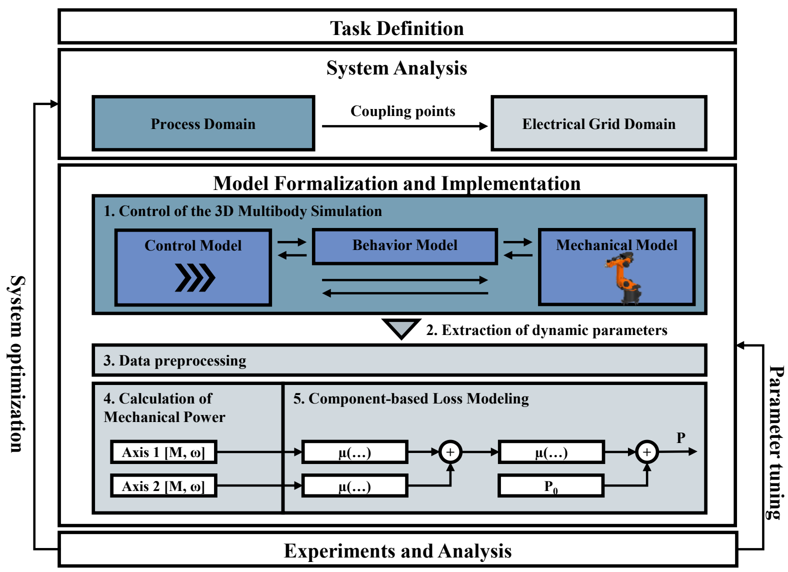

Figure 2: Methodology.

The first step in the proposed methodology is the task definition, where the specific objectives of the simulation are outlined. In the context of component dimensioning within the electrical grid, information about the relevant power ranges of the production system is particularly important to ensure appropriate sizing. Other objectives may include reducing energy demand through appropriate parameter adjustments, e.g. reducing concurrency factors in the control code of the overall system and reducing peak loads in the process domain or evaluating energy management concepts within the power grid.

This step is followed by the system analysis, in which the system is examined based on the relevant elements required to address the defined objectives. In particular, it is necessary to identify the required interfaces and the key components relevant to the analysis, as well as to consider their coupling points with the energy grid. This results in a first conceptual model of the system.

The next phase, after the creation of the conceptual model, is the formal model development and implementation within an executable simulation environment. This methodological part is structured into the following five steps:

1. Control of the 3D multibody simulation
2. Extraction of dynamic parameters from relevant elements
3. Data preprocessing
4. Calculation of mechanical power
5. Component-based loss modeling

The first step involves the utilization of existing VC simulation models of the system. These are typically characterized by three core components:

- The mechanical model, which describes the masses, kinematics, and motion ranges of the system
- The control model, which reflects the logical sequences or the PLC program
- Behavioral models, which represent specific physical (e.g. drive controls) or communication (e.g. time deviations due to ethernet) properties

In subsequent energy evaluation, it is important to ensure that mass and inertia properties are accurately assigned in the mechanical model. These parameters are typically automatically derived from material definitions in standard CAD tools, or provided directly from supplier model libraries.

In the data preprocessing step, the raw motion data (forces, torques, velocities) is first denoised using a low-pass filter to eliminate numerical artifacts. Subsequently, coordinate transformations are applied to align the motion vectors into a common reference frame. Based on the transformed data, the mechanical power for each axis can be calculated:

$$P_{mech} = \begin{cases} \vec{F} \cdot \vec{v}, & for\ linear\ motion \\ \vec{M} \cdot \vec{\omega}, & for\ rotational\ motion \end{cases}.$$

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This mechanical power is used as the basis for component-based loss modelling. For each axis under consideration, a block diagram is constructed that systematically represents all relevant energy conversion and transmission stages and their efficiency in the scope. The approach is based on an adapted methodology described in Gutwald et al. (2023). To model both energy consumption and recuperation in a unified manner, a direction-dependent efficiency function is introduced. This function maps input power to output power and reflects conversion losses based on the direction of energy flow.

$$P_{out} = \mu(P_{in}) \cdot P_{in}\ with\ \mu(P_{in}) = \begin{cases} \mu^{-1} > 1 & for\ P_{in} \geq 0\ (Consumer\ Mode) \\ 0 < \mu \leq 1 & for\ P_{in} < 0\ (Recuperation\ Mode) \end{cases}$$

In consumer mode (positive mechanical power), the system consumes electrical energy, and conversion losses are accounted for by dividing the mechanical input by the efficiency. This results in an apparent efficiency >1 if defined as μ(Pin)=Pout/Pin, reflecting the fact that more electrical power must be supplied than mechanical output is delivered. In recuperation mode (negative mechanical power), the mechanical system returns energy to the grid. In this case, the same efficiency function applies but without inversion.

This modelling approach enables the representation of the entire loss chain in a generic manner, with a minimal requirement for parameterization or the need for complex behavior models. The end result of this model is the electrical power required by the process participants,

Based on the resulting load profiles, experiments can be conducted according to the aim of the simulation. The individual parameters of the loss functions can be calibrated by comparing them with real data of the system, in order to generate stable and realistic results. Furthermore, in line with established simulation methodologies, proper verification and validation of the individual simulation artifacts must be ensured.

4 CASE-STUDY: DC-DEMONSTRATOR

In order to demonstrate the proposed methodology, this study aims to model the energetic behavior of a demonstrator in order to realistically estimate the load on individual grid branches. The involved system components are analyzed and modeled separately. The first use case focuses on a 4.35-meter-high lift tower, designed as a regenerative load and capable of operating in both AC and DC modes. The second use case involves a 6-axis industrial robot (KUKA KR30), which has been adapted for operation within a DC Grid.

4.1 System Analysis

The 4.35-meter-high lift tower is designed for small load carriers (600 × 400 mm) with a maximum weight of 60 kg. The drive system consists of two Lenze i550 motec controllers (each rated at 1.5 kW): one is a conventional AC frequency inverter with regenerative capability, and the other is a modified prototype for DC grid operation, equipped with electronic protection, pre-charging technology, and regenerative feedback.

The six-axis industrial robot used in this setup is a KUKA KR 30/2, featuring a nominal payload of 30 kg and a total installed motor power of approximately 12.5 kW. The robot is operated via a KUKA KR C2 controller and is suitable for a wide range of path-controlled applications. Axes A1 through A6 are driven by AC servo motors equipped with integrated brakes and resolvers. Due to the lack of modern communication interfaces, the connection to the Siemens S7-1500 PLC is established via digital input/output peripherals. All motors are interconnected via a common DC intermediate circuit, which allows for regenerative energy exchange between the individual axes. The KUKA PM6-600 power electronics module is protected by a functional safety chain, overcurrent protection, and additional shutdown relays. The wiring to the control cabinet and subsequently to the power module is designed for operation on a 3-phase 400 V AC power supply. By directly connecting into the DC intermediate circuit and implementing the appropriate protective circuitry as described in Gutwald et al. (2024) a switch from AC to DC operation is realized.

The following figure illustrates the conceptual structure of the experimental setup. Both system participants can be operated via either the AC or DC grid, while switching between both is possible. The process is controlled by a Siemens S7-1500 PLC. Each component is powered via the same AC or DC grid. The starting point of the real measurements is shown in Figure 3, which means that all mechanical and electrical losses occurring up to these measuring points are considered in the case-study. For the robot, three specific motion sequences are examined: a vertical, a horizontal, and a diagonal movement. An attachable weight plate at the end-effector allows the additional payload of the robot to be varied. The lift tower follows a defined motion cycle from bottom to top and then back down again.

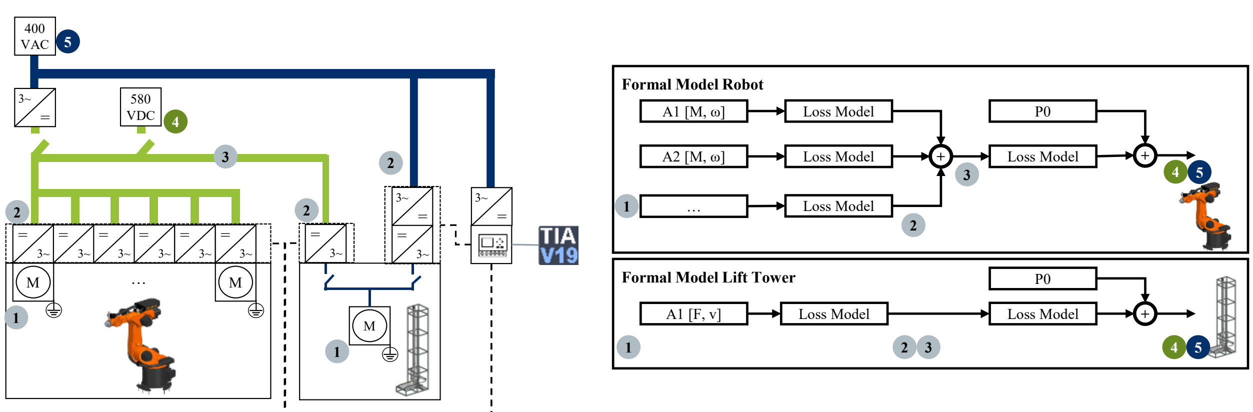

Figure 3: Formal model.

4.2 Software Architecture

The implementation of the simulation model was realized using a software-in-the-loop (SiL) integration with the respective tools as shown in Figure 4. The control programming was executed using Siemens TIA Portal V19 which was emulated on the PC using PLCSim Advanced V6.0, the physics-based 3D simulation was conducted with NX MCD (version 2212), and the behavior and energy modeling of the loss functions was performed with Simit 10.

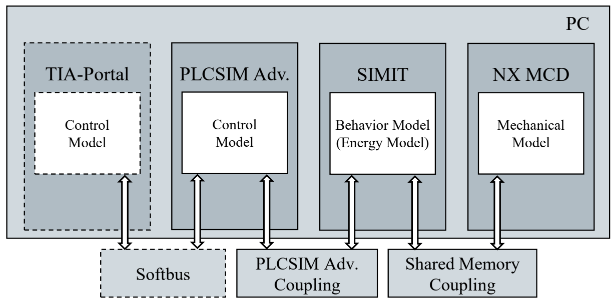

Figure 4: Software structure.

4.3 Model Formalization and Implementation

The system is formalized according to the methodology illustrated in Figure 2. For this purpose, the existing models for VC in NX MCD and TIA Portal are utilized. These models are kinematically defined by fixed parameters, including mass properties and kinematics. Motion control is implemented via the control code in TIA Portal, which realizes four distinct motion sequences. M1 describes a horizontal rotational movement of the robot, M2 a vertical movement, and M3 a diagonal motion that exemplifies a typical pick-and-place operation. The lift tower executes a translational up-and-down movement, designated as M4. Both the robot and the conveyor tower allow for variable configuration of the attached masses and the associated velocity profiles.

The formal model of the electrical grid connection is developed and implemented up to the defined measurement points in SIMIT, which are depicted in Figure 3.

The Losses are represented using the corresponding efficiency functions. The conversion between points 1 and 2 in Figure 3 reflects the transformation of mechanical energy into electrical energy along a given axis. The efficiency function represents a direction-dependent efficiency that accounts for all mechanical and electrical losses up to this point. Within the case study, constant efficiency values were applied independently of the operating point to ensure low modeling effort especially in the early design stages: μ_1 for consumer operation and μ_2 for recuperative operation. For Axis 1 of the robot, these were set to 50% and 35%, respectively. For increased modeling precision, more complex loss models, such as those proposed by Paryanto et al. (2015), can be employed; however, these are in contrast to the objective of minimal parameterization.

The transition from point 2 to point 3 represents, in the case of the robot, the flow of energy from an individual axis to its intermediate DC link, which aggregates the power of all axes. Positive power values are interpreted as energy consumption from the grid, whereas negative values represent recuperative energy flows, which are accordingly balanced in the intermediate circuit. The subsequent transition from this point to measurement points 4 in the DC grid and 5 in the AC grid includes all additional conversion losses caused by protective components and power transmission. If regenerative capability is not required, the corresponding efficiency μ_2 in the loss model should be set to 0%. Furthermore, standby power consumption (e.g., due to control systems) is accounted for by adding a constant no-load P_0.

The initial parameterization of the loss models is based on estimations derived from literature values and datasheets. These parameters can be refined using measurement data obtained from the actual system or a comparable reference system.

4.4 Experiments and Analysis

The setup for each experiment includes the attached masses and the velocities of the system components. Additionally, the type of grid connection, either DC or AC, was varied as a factor. This distinction results in different efficiencies for the corresponding loss models (point 3 to 4/5 in figure 3). The full-factorial experimental plan was executed both on the real system and within the simulation model. Power profiles over time were recorded as results for each experiment. In the context of sizing the electrical components, particular attention must be paid to both the peak power and the peak-to-peak range. From an energy optimization perspective, the recuperation energy is also a key factor.

Results from selected experiments are shown in the figures below. Blue lines indicate AC grid connection, while green lines represent DC. Solid lines correspond to data collected from real-world experiments, simulated results are indicated by dashed lines.

The findings demonstrate a sufficiently accurate matching between the simulated and measured values. However, temporal shifts in the load profiles are present, which can be explained by discrepancies between

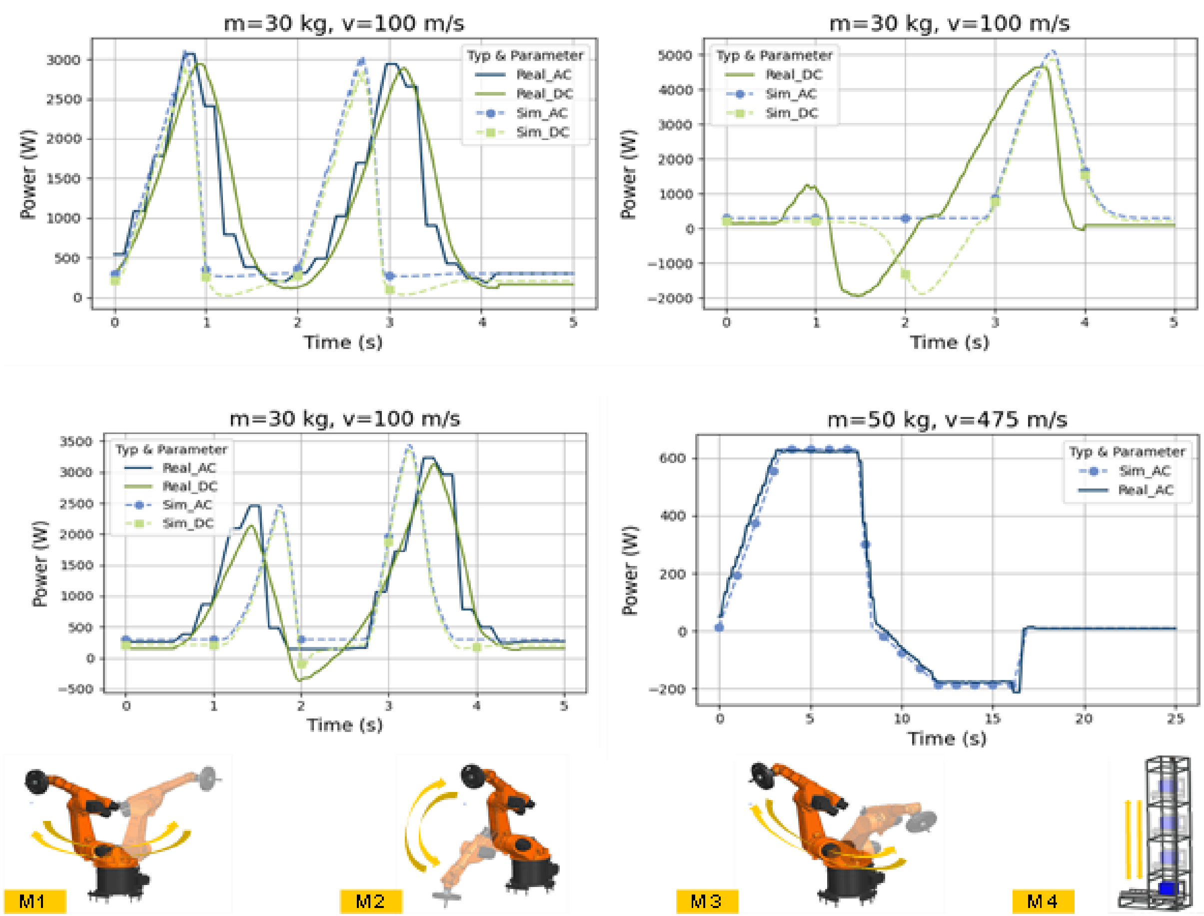

Figure 5: Load profiles resulting from the experiments: Top left – M1 (Robot, Horizontal), top right – M2 (Robot, Vertical), bottom left – M3 (Robot, Diagonal), bottom right – M4 (Lift Tower).

the control behavior of the real and the simulated robot. Despite these temporal discrepancies, the magnitude of power consumption aligns reasonably well throughout the experiments.

Given that a full-load scenario was used in each experiment, it is seen that the robot reaches a maximum simulated power of about 5000 W, while the lift tower maximum is about 650 W. The current real system is designed for 12.5 kW for the robot and 1.5 kW for the lift tower. This results in an oversizing factor of about 2 for the real system. This indicates potential for cost and efficiency optimization.

5 DISCUSSION AND CONCLUSION

The presented results demonstrate that load curves can be reproduced with sufficient accuracy to support early-stage design decisions. Based on the simulated energy behavior, components can be realistically dimensioned according to the expected power. The method offers a straightforward and effective approach for estimating the power behavior of mechanical components using only a minimal set of parameters. It is particularly well-suited for preliminary planning stages and can be efficiently combined with existing models from process or mechanical engineering disciplines used in VC.

The proposed modeling approach can be extended to more complex systems involving multiple consumers, such as a line of industrial robots. In such configurations, energy exchanges between individual robots can be captured. This enables the integration of energy-aware control strategies directly within the process simulation, such as load shifting to reduce peak demand. As a result, realistic simultaneity factors can be derived, allowing for the downsizing of central electrical components like Active-Front-Ends in the DC grid. Moreover, the simulation of multiple loads enables a more accurate estimation of peak loads and their probability of occurrence, which further improves grid dimensioning. Additionally, the method allows for the evaluation of energetic impacts on existing infrastructure, providing insights into how the addition of new system components may affect current grid utilization.

Building on the process simulation, the coupled electrical grid model, which is described more detailed in Barth et al. (2024) enables more detailed analysis of temporal dynamics and power losses. Electrical switching and protection functionalities can be realistically represented and incorporated into system-level design considerations. Furthermore, the method facilitates the integration and assessment of energy management strategies, such as droop control for efficient battery control. The use of ultracapacitors for buffering short-term peak loads can also be investigated. Overall, the simulation framework supports comprehensive evaluation of grid stability, responsiveness, and system autonomy.

Despite its advantages, the method has limitations. It is restricted to mechanically driven components, and thus, energy-intensive process operations such as welding cannot be modeled with this approach and require alternative techniques. Additionally, due to the chosen level of abstraction, certain electronic phenomena remain unconsidered. In one experiment, a rapid vertical motion (Experiment M2, 100% velocity) in AC operation resulted in an overvoltage event that triggered a system shutdown—an effect not represented in the abstracted simulation model. The influence of the control program also plays a significant role in the accuracy of the results. In the presented study, the real robot control system did not precisely match the simulated control implemented via TIA Portal and NX. This led to temporal mismatches and an incomplete representation of robot dynamics. For realistic implementation, it is therefore essential to align the simulation control logic as closely as possible with the real system's execution behavior.

Future work will focus on integrating the proposed approach into the DCign simulation framework, introduced in Barth et al. (2024). By simulating the energy demand of production systems and analyzing hybrid AC/DC grids, this framework aims to support the modular configuration and dimensioning of DC-based production systems. It enables the design of economical, safe, and regulation-compliant systems while utilizing the ecological benefits of DC grids. This will support broader adoption of DC technology as a key enabler for carbon-neutral manufacturing.

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