Method for energy-efficient assembly system design within physics-based virtual engineering in the automotive industry

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Abstract

Automated assembly systems in the automotive industry require thorough virtual validation procedures complementary to early design stages and prior to commissioning and ramp-up. This contribution introduces a conceptual method to assure an energy-efficient assembly system design within the virtual validation procedure Virtual Engineering as pre-process to Virtual Commissioning. As initial step of the method, relevant system planning data (sequence diagram, BOM, etc.) is analyzed in order to identify energy consumption units (ECUs) and their activities in the manufacturing process. Subsequently, physics-based simulation capabilities based on game engine technology are used to model individual ECUs (electric motors, pneumatic drives, robots, etc.) of the production system and the entire manufacturing process in a virtual 3D-CAE simulation environment. The simulation delivers energy signatures of both the entire production system on an aggregated level as well as on an individual ECU-level. Based on this data, energy efficiency improvement measures are implemented and validated in the virtual model of the assembly system. This entails an energy-efficient production system design while maintaining predefined production system settings like cycle-time and output. The conceptual method is exemplified by a use case of an automated assembly system from the automotive industry presenting preliminary results.

Keywords: Energy-efficient processes and systems; Sustainability of manufacturing systems; Automated production systems; Virtual commissioning; Physics-based modeling

1. Introduction

Nowadays, highly automated production processes in automotive industry account for substantial amounts of energy consumption [1]. For industrial customers electricity prices and cost for energy procurement have steadily risen over the last decade in Germany [2]. Political directives for primary energy consumption and CO2-emission force Original Equipment Manufacturers (OEMs) to streamline their production processes [3, 4]. In addition, growing environmental awareness among customers increases demand for environmentally sound manufactured automobiles. Those economic, political and market catalyst have drawn OEM’s attention to establish environmentally sustainable production processes.

Many significant parameters determining a production system’s energy consumption in the operating phase are defined in early system design [5]. State-of-the-art tools of the Digital Factory for production planning, production system design and virtual validation insufficiently consider features for production system’s energy consumption forecast [6, 7]. Capabilities for production system’s energy consumption prognosis based on digital prototypes would enable OEM’s production planner to precociously secure energy-efficient system design and thus reduce operating cost and CO2-emission. A conceptual method for realizing energy-efficient production system design within virtual validation based on an innovative simulation approach is presented and in extracts exemplified in this contribution.
2. Virtual Validation Procedures of Production Systems

Two virtual validation procedures industrially deployed for automotive production systems are presented and physics-based virtual validation of production systems is introduced.

2.1. Virtual Engineering and Virtual Commissioning

The development process of automated assembly systems requires close collaboration among OEM’s production planning department, plant manufacturer (PM), and specialized subcontractors. Early in the development process virtual 3D-CAD models of the production system and its components enable locally distributed engineering and ease coordination. The model’s level of detail continuously advances underpinned by collaboratively made design decisions. Based on those 3D-CAD models, tools of the Digital Factory are concurrently applied to virtually validate the production system’s layout and design (cf. Fig. 1).

At Daimler two validation procedures are well established for body-shop systems and have been tentatively applied to automated assembly systems in recent years. The procedure Virtual Engineering (VE) utilizes an enriched 3D-CAD model of the production system for visualization and simulation-based validation of system processes, product-system-interactions, cycle-time and collision-avoidance for different product-variants [8]. Simulation of the desired process sequences enables mechanical validation of the system layout and the respected component designs and must be delivered by the PM in order to receive OEM’s mechanical design approval [9, 10]. Based on a mechatronic system model the procedure Virtual Commissioning (VC) aims at validation of the system’s control software by connecting the Programmable Logic Controller (PLC) to virtual production system models via Hardware-in-the-loop (HiL) with respect to real-time restrictions. VC permits precocious evaluation of the entire production system and system processes, in particular electric signal exchange and control software testing [11]. Successful VC precedes software design approval for the PM issued by the OEM’s production planning department.

Both procedures are continuously advancing and are subject of several research activities in industry and academia. Main efforts are directed to increase level of maturity and quality of virtual simulation models, eliminate disruptions in the tool chain, and standardize data exchange formats, e.g. [12].

Fig. 1. Design and virtual validation of automated assembly systems

2.2. Physics-based Virtual Validation of Production Systems

One approach for increasing level of maturity and quality of the simulation models for virtual validation procedures is to append physics-based simulation capabilities. Physics-based simulation features dynamic multi-body simulation approximating physical phenomena of rigid bodies, soft bodies or particles [13]. Incorporating a ready-to-use software library (physics engine) that efficiently computes differential equations based on Newtonian mechanics results in realistic object movement and interaction in the simulation scene. Commercial or open source physics engines originate from gaming industry but become more widespread in scientific tools to simulate and validate production systems.

Research activities with respect to physics-based VC focus different aspects of validation within the development process of production systems. Significant efforts were directed to establish a methodological foundation in order to establish physics-based VC for different production system types, e.g. [14, 15]. The integration of precocious physics-based robot program development and validation has shown promising results and industrial applicability [16, 17]. Physics-based VC for sophisticated material flow simulation offers significant benefits in particular for bulk materials, e.g. [18, 19]. Raising acceptance for physics-based production system simulation is further proven by vendors of commercial tools enhancing their solutions with physics-based simulation features.

3. Energy-Efficient Assembly System Design within Physics-based Virtual Engineering

The following section introduces an innovative method to virtually validate an automated assembly system for the automotive industry with respect to energy-efficiency design criteria. Initially, the entire method is outlined followed by a detailed description of each individual stage.

3.1. Method outline

The method encompasses five process stages with individual subtasks substantiated by the results of the preceding stage and its respected tasks (cf. Fig. 2). Several supportive production planning documents are also required in order to implement the suggested method.

Virtual 3D-CAE simulation models originating from conventional CAE-tools utilized in the automotive industry (e.g. DELMIA V5, Process Simulate, etc.) serve as input and are further processed. Generally, those models must be provided by the PM and their structure and nomenclature are explicitly designed according to OEM’s specifications. The final outcome of the entire method are two physics-based virtual 3D-CAE models of the designated assembly system, one with the original system design and the other featuring some design improvements in order to increase the energy efficiency of the entire system design. Both system designs are further supplemented by individual lifecycle comprising cost analyses devoted to serve as decision support for OEM’s production planning department.
3.2. Energy Component Modeling

For analyzing the system design with respect to energy consumption in the first place the individual ECUs (Energy Consumption Units) must be identified based on available planning documents. Generally, the PM must provide a BOM (bill of materials) of the assembly system based on the mechanical plant layout. The BOM (system components list) shortlists all components interacting with the PLC via electric signal exchange, thus encompassing all sensors (e.g. distance sensor) and actuators (e.g. electric and pneumatic drives). Based on that and corresponding planning documents the required ECU-models can be identified. Additionally, the conventional CAE-simulation model must be transferred to the physics-based simulation environment. Here, standardized data formats like AML and COLLADA secure raw layout data import without significant information losses. For proper ECU modeling the models must be further enriched with dynamic properties (masses, moments of inertia, etc.) and kinematic constraints (joint position, joint range, etc.). Those parametrization activities require substantial manual modeling efforts and depend highly on the user’s skills and experience.

Based on the identified ECUs it must be decided upon the ECUs to be modeled in the physics-based simulation environment. The set of the identified ECUs can be clustered according to their type of energy consumption in constant and variable ECUs. Contrary to variable ECUs, constant ECUs offer often only very limited potential to be adapted in order to increase energy efficiency and must solely be modeled on rare occasions. Energy consumption of ECUs required for joining two product parts might be represented by a simplified model. However, since joining technologies (e.g. welding, screwing) are specified based on product characteristics, they are not modifiable and out of scope for energy consumption optimization. Parameters determining energy consumption of relevant ECUs must be extracted from data sheets provided by the ECU manufacturer or must be identified by parameter identification experiments. After parameter identification the physics-based modeling of the respected ECU is realized via script-based coding delivering the correct energy consumption behavior of the ECU. Upon this process stage’s completion all ECUs are available as energy component models representing their correct physical and energy consumption behavior.

3.3. Energy System Modeling

Based on individual physics-based energy component models the entire production system model can be composed, resulting in a physics-based system energy model. Additional simulation entities in order to aggregate and visualize the energy consumption of the entire assembly must be implemented. Furthermore, the assembly process must be modeled based on the information of the sequence diagram. In particular, precise ECU activities can be extracted by analyzing the individual assembly tasks (positioning, transporting, joining, etc.) in the sequence diagram. In addition, CAD product data is required in order to model the entire assembly process properly.

As a consequence the assembly process can be modeled in the physics-based simulation environment resulting in an initial energy signature of the assembly system. The energy signature depicts the amount of energy that must be supplied in order to execute the assembly operations (AO) successfully. The initial energy signature represents the prognosticated energy consumption of the initial assembly system design and encompasses volumetric flow [m³/s] required by all pneumatic components and apparent power supply [W] over time, respectively (cf. Fig. 3). Both quantities

![Fig. 2. Conceptual method for energy-efficient assembly system design within physics-based Virtual Engineering](image-url)
complemented by their integration over time in terms of total volume of compressed air consumption [m³] and total amount of energy consumed [kWh] serve as indicator to quantitatively access the energy efficiency of the assembly system.

3.4. EEIM Analysis

Based on the physics-based system model and the resulting initial energy signature of the assembly system energy efficiency improvement measures (EEIMs) must be implemented. Multiple measures originating from different fields of research and best practices extracted from industrial application have been identified and composed in a list of potential EEIMs (EEIM catalog). The EEIM catalog features four categories with respect to the essential modifiable ECU's of automated assembly systems (electric motors, pneumatic drives, robots) plus a category to optimize the entire assembly process. An analysis in order to examine the EEIM’s applicability for the considered assembly system must be carried out. The task of EEIM selection and testing must be executed manually and depends highly on the individual initial system design and the user’s skills and experience.

Initially, potential for optimization must be identified in a structured manner. There are several options to approach energy consumption optimization, for example by building Energy-KPIs and focus on ECU's or assembly operations with the major share of total energy consumption. Alternatively, “waste” within the assembly process can be addressed first, conducting energy value stream mapping applying Lean Management techniques [20]. This waste could be non-value adding (tool) movements or unproductive idle periods. Subsequently, potential EEIMs must be mapped with the waste identified from the energy system model. A rough estimate of the potential EEIM energy saving benefit must be quantified based on the individual scenario. Those EEIMs serve as remedies for avoiding the identified waste and must be manually selected from the EEIM catalog.

Consequently, the system model is mapped to EEIM catalog by linking individual EEIMs to energy component models. Further investigations must be undertaken about additional information required in order to implement selected EEIMs and involved modification effects (e.g. design adjustments). EEIMs might be ranked according to the tradeoff between estimated beneficial energy saving effects (probable amount of waste vanished) and the estimated EEIM implementation activities required (e.g. effort for design modifications to implement EEIM). The process stage’s outcome is a prioritized list of feasible EEIMs supplemented by required information and efforts to realize design adjustments.

3.5. Feasible EEIM Implementation

Based on the list of feasible EEIMs implementation is conducted starting with the most promising EEIM. Ideally, the implementation can be realized by adjusting parameters of the physics-based energy component models (e.g. electric/pneumatic actuators) or minor adjustments in driver operation characteristics (e.g. trajectory optimization). Examination about significant reduction of the component’s individual energy consumption precedes examinations on system level whether the component’s dedicated functionality can still be realized without violating system’s boundary conditions. If it is possible to implement the respected EEIM on the system’s level, the energy saving benefit must be economically quantified. Cost for EEIM’s implementation activities (e.g. higher material cost, additional engineering hours, etc.) must be estimated and traded off against potential energy savings for subsequent economic evaluation of the energy-efficient system design. Generating the optimized energy signature by running the energy-efficient physics-based system model and comparing both energy signatures enables quantitative assessment of the consolidated beneficial energy savings.

3.6. Economic Analysis

The final process stage requires both energy signatures as inbound information, aggregated EEIM's implementation costs, and additional specific planning and economic information (e.g. system lifespan, load factor, investment cost etc.). This information enables a holistic lifecycle cost assessment (e.g. Life Cycle Costing analysis) of the assembly system for both different system design alternatives [21]. Based on experience the energy-efficient design features most probably lower operational costs due to lower energy costs assuming consistent maintenance cost while requiring higher investment costs. Ultimately, the aggregated information provided for both design variants enables OEM’s production planner to decide upon the economic most beneficial design variant with respect to the system’s projected operating phase.

4. Method Application for a Use case

The conceptual method is exemplified in extracts on an automated assembly system that consist of multiple pneumatic drives and several electrical motors. In particular, the conceptual method’s process stages energy component modeling, EEIM analysis, and feasible EEIM implementation are briefly presented.

The system component list specifies all the system’s components and is used as starting point for energy component modeling. One item on the list is a three-phase AC motor (ASM) that is modeled in combination with frequency

![Fig. 4. Schematic energy component model of a three-phase AC motor](image-url)
inverter and helical-bevel gearbox. Dynamic data ($\tau_l$ - mechanical torque, $n_l$ - rotation speed) is provided by the physics-based simulation environment, motor parameters ($n_n$ - nominal rotation speed, $U_n$ - nominal voltage, $\eta_n$ - nominal motor efficiency, $\eta_g$ - nominal gear efficiency, $\cos \phi$ - power factor) are extracted from the component’s supplier data sheet (cf. Fig. 4). Some physical relations (power factor linearly depends on rotation speed, motor efficiency linearly depends on rotation speed) are simplified and assumed in order to model transient states. Outbound parameters are power consumption ($P_a$ - active power, $Q$ - reactive power, $S$ - complex power) of the motor for the respected simulation time step $\Delta t$.

**EEIM analysis** based on the assembly system’s initial energy signature reveals a peak in power consumption for two assembly operations executed simultaneously by two three-phase AC motors. The process sequence bears some unproductive idle periods and there is no technical link between both motors so that both operations must not be started simultaneously. From the EEIM catalog (cf. Fig. 6) the category peak power reduction within the item process featuring the measure of sequential ramp-up is selected for feasible EEIM implementation. As a consequence, both motors ramp up with a time offset, so that the power peak is suppressed (cf. Fig. 5). Peak power consumption is reduced resulting in a more energy-efficient design.

No design adjustments must be implemented due to use of the same layout and hardware. Cost for EEIM implementation activities can be neglected.

**5. Conclusion and Outlook**

This chapter encompasses a brief summary of the presented method and gives an outlook for subsequent research activities.

**5.1. Summary and results**

This contribution presents a novel conceptual method for energy-efficient system design of automated assembly systems in the automotive industry within the validation procedure Virtual Engineering using physics-based simulation capabilities. The method consists of five process stages and corresponding subtasks starting from the assembly system’s conventional 3D-CAE model. Based on a structural analysis the system’s ECUs are identified and modeled within the physics-based simulation environment with respect to their physical and energy consumption behavior. Employing additional planning information the entire assembly process is modeled resulting in the system’s energy signature that maps energy consumption in terms of volumetric flow and power consumption to the respected assembly operations. Four different categories of energy efficiency improvement measures are then analyzed and individually scanned for applicability in the considered assembly system. Feasible EEIMs are subsequently implemented in the physics-based virtual system design and tested if mechanical validation criteria are still met. Further design implications for EEIMs’ implementations must be taken into account and evaluated. Ultimately, an economic analysis considering the entire lifecycle of the assembly system is carried out including not only investment cost but also operation cost with respect to energy cost. The method results in an evaluation of the initial and the energy-efficient system design in terms of energy consumption and enables OEM’s production planner to determine the economic and ecological most beneficial design variant.

The conceptual method is exemplified in extracts on a use case of an automated assembly system. A three-phase AC motor is modeled in the physics-based simulation environment. Based on an analysis of the assembly system and the assembly process one energy efficiency improvement measure was identified and implemented in the system resulting in significant peak power reduction.

**5.2. Outlook and potential for future research**

For exploring the entire potential of the introduced method for industrial utilization and for integration into current production planning business processes several requirements must be considered.

With respect to technical implementation some ECU models are still work-in-progress and must be continuously improved and refined. Whereas the models’ qualitative validation is completed quantitative validation still remains. The desired outcome is a ready-to-use ECU-model library composed of the most frequent types of ECUs implemented in automated assembly systems. This model library must be made available for state-of-the-art 3D-CAE simulation.
environments featuring physics-based simulation capabilities. Further support for automated system model generation would ease simulation set-up. The EEIM catalog must be formalized and user-friendly provided. The significant manual effort for EEIM analysis and EEIM implementation shall be reduced by establishing algorithms for identifying potentials for energy consumption optimization. Capabilities for automated economic evaluation and comparison for different system designs based on energy consumption and lifecycle planning data must be established.

Regarding organizational aspects conditions for industrial application have to be defined in order to integrate the method into current business processes. Responsibilities on the OEM’s and PM’s side must be specified and energy-efficient system design adequately rewarded in the bidding process. In order to foster energy-efficient system design, guidelines for energy-efficient assembly system design can be issued by the OEM’s production planners. Ultimately, to ensure the conceptual method’s industrial applicability, it must be verified on a real business case along the entire development process of an automated assembly system.

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