Resource and energy efficient process integrated development with virtual prototypes for mobile machinery

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Abstract

Environmental protection, rise of energy-costs, economic crisis – mechanical engineering is forced to come up with innovative and sustainable concepts to keep up with competitors. This has a notable impact especially in the branch of mobile processing machinery. Besides such directives like the emission-directive for mobile processing machinery, which is becoming effective, the EU stated the goal of reducing, the emission by 20 %.

To meet the legal requirements considering the increasing variety of concepts for power-transmission a methodology and an analysis-tool for development and evaluation of energy-saving drivetrains are required. This objective is the concern of the research-project ENPROVI supported by the Federal Ministry of Research and Technology. Besides the lead partner Forschungszentrum Karlsruhe (PTKA) the development proposal is carried out together by the associated partners ITI GmbH, TAKRAF GmbH and TU Dresden (IVMA-BFT). The ITI GmbH supplies the computing platform for the realisation of the analysis tool “Power Balance” in terms of SimulationX®. The new feature “Power Balance” can be used to investigate power flows and energy consumption in model of technical systems. It describes how powers are calculated, categorized and summed with the help of the Power Balance. The practical application of the analysis tool is tested by means of a demonstrator model of the TAKRAF GmbH.

KEYWORDS: BMBF-project ENPROVI, simulation, power calculation, energy efficiency, mobile processing machine

1. Issue

The manufacturers of mobile processing machinery have to choose from a large variety of system solutions for the powertrain. Their only common feature is the diesel engine as a power source. Mostly branch-specific tools, which do not allow extensive investigation of the overall efficiency, are used for the solutions design and calculation. From the todays point of view there is no way to measure the demand for energy and the process-related load spectrum.

These issues will gain relevance regarding to fuel costs and the strict regulation of exhaust emissions. To allow the investigation on efficiency, it is necessary to provide an analysis tool for the profound and systematic examination of the energy consumption and the emissions at disposal.

2. Methodical approach for the energy- and pollutant balance

The objective of the suggested analysis procedure is a process-related evaluation of the energy- and pollutant issues for mobile processing machinery. The basis thereof are models for a “reference machine” and a “reference process”. Reference in this context means the relation between the real processing machine and the process, respectively. The crucial approach to achieve this objective stated is the coupling of both reference models. An information exchange between both models is possible via a feedback coupling. The communicated parameters represent flow- and potential variables - power and speed, volumetric flow and pressure, and so on - from all physical domains. The realization of the coupling takes place by means of an external control-loop, representing the human characteristics of the user.

The basis of the process dependent assessment of the energy consumption is formed by the model “reference process”. The main goal of the modeling is the calculation of the partial process performances (flow- and potential variables) as well as the technological performance - it describes the effective performance output in relation to a representative operation cycle. By means of the model “reference machine” both performance characteristics and consumption of primary energy are determined. The process-related performance characteristics as there are power intake, stored power (both capacitive and inductive) and dissipated power reflect the component- and system dependent attributes (effectiveness), i.e. by means of these information conclusions on optimization potentials can be drawn. The calculation of the primary energy requirement (fuel consumption of the diesel engine) demands the modeling and implementation of a primary energy source. Using the deployed coupling of the models the required energy for executing a certain task is related to a defined process performance.

For the evaluation and the comparison of the process-related energy requirements of one single “reference machine” or multiple machines among themselves, respectively, a quality criterion is required. The criterion used in this approach is the specific use of primary energy. It represents the relation between a defined technological performance and the calculated process-dependent primary energy consumption. On a surface miner, this would be the fuel intake in relation to the rock cut (l/m³).

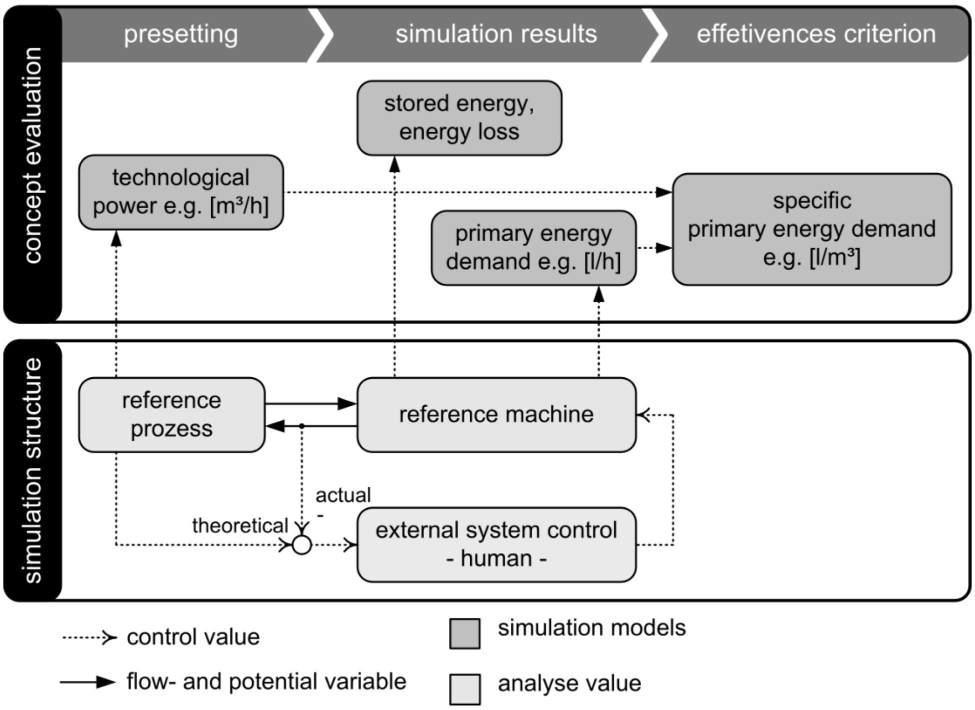

Figure 1: Methodology of resolution and simulation structure

3. Modeling of the reference process

Due to their design mobile processing machines can perform a great variety of tasks. These machine-specific processes consist of static and transient process fractions. The execution of such a task is accomplished by means of several individually driven actuators. Hydraulic cylinders and hydraulic motors are examples therefor. Hence a structured approach is required to describe such typical, process-related properties, a generally valid model structure is needed.

At first, for the development of the “reference process”, the machine-specific process, a technologically representative task performed during one working cycle, needs to be determined. For the surface miner possible milling technologies depict its process patterns. By the choice of a specific pattern, certain information about the process is determined, e. g. the width of the milling track. Thus the edge conditions of the reference process are defined. The next step in modeling includes the definition of the temporal sequence of motion(s) performed by each single actuator during a work cycle. Subsequently, the machine specific resistances originating in the process need to be generated. They are determined by the earlier identified motion pattern of the actuators and can be computed or measured. While the translations and rotations of a mass are easy to calculate by means of analytical descriptions, forces originating in the interaction with the soil, e. g. digging, are nowadays still measured.

By depicting the process fractions and the working resistances, powers in those fractions are determined. They are the product of the process-related flow- and potential variables which are simultaneously the parameters exchanged by the reference models “process” and “machine”.

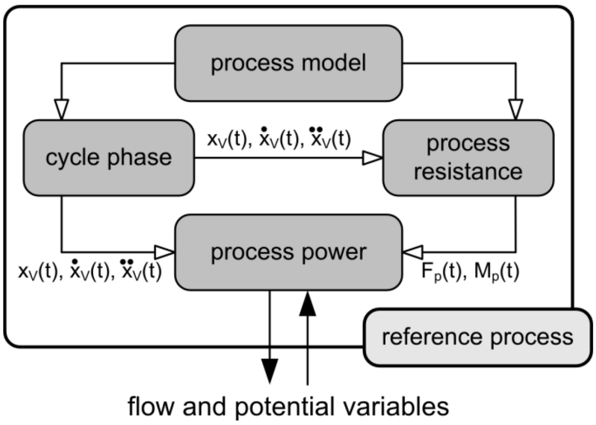

Figure 2: Model structure – reference process

4. Modeling of the reference machine

Because of the large variety of designs of power trains, certain requirements are to be met by an analysis-tool. For analysis, assessment and optimization of the process-related efficiency the flow of power or energy, respectively, within the “reference machine” needs to be computed. It is not sufficient to know the total energy requirement of the whole machine. It is rather necessary to determine the power flow in the single components and parts of the power train. Therefore the submodels of the “reference machine” should be structured with focus on functionalities/ components, i. e. comparable and interchangeable. In addition to the power train the primary energy source and the structural mechanics of the “reference machine” need to be depicted. That is the only way to consider process-related interactions of the different parts of the power train when assessing the efficiency.

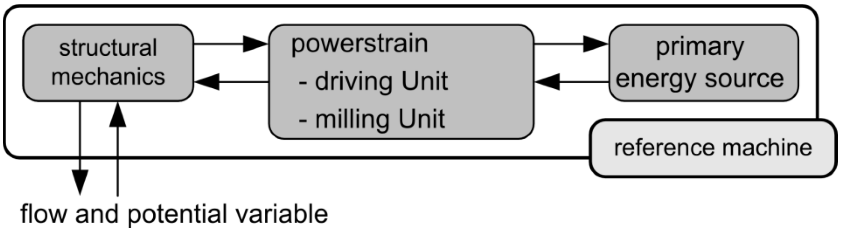

Figure 3: Model structure – reference machine

Illustration 4 depicts the simulation model for the front left traction drive in the system simulation software SimulationX. The modelling was realized with regard to both a hierarchical and function oriented structure of the model. By means of the integrated algorithm the power and energy flows could be determined and provided for every level of the model. As an example, the properties of the hydraulic transmission are shown.

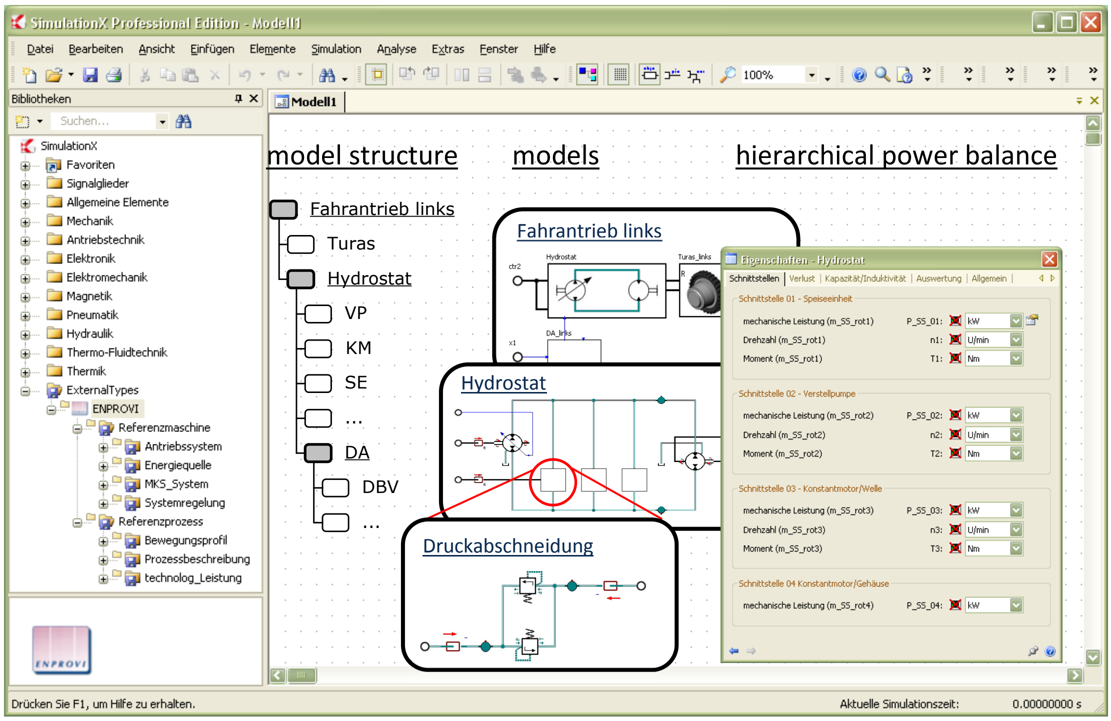

Figure 4: Example – Simulation model “Fahrantrieb links”

5. Power Balance in SimulationX

The Power Balance in SimulationX 3.5 is a new feature which may help the user to investigate power flows and energy consumption in models of any technical system.

The power P can be calculated in different physical domains with the corresponding flow quantity Fq, e.g. a mechanical force, and the potential quantity Pq, e.g. the velocity:

$$P = Fq \cdot Pq \tag{1}$$

With that general formula all occurring powers can be calculated at the basic model elements in SimulationX libraries. But why is it not sufficient to simply measure the power flows between components or parts of the technical model, e.g. the inflowing and outflowing powers into a gearbox? The answer is quite simple, because that measurement cannot answer the question what happens with the power in the component or the model part. It might be stored, e.g. by speeding up a rotating inertia or tensioning a spring, or it can be lost, e.g. due to friction. Stored energy in contrast to lost energy can be used later in the working process. So this categorization of occurring powers according to their type can only be done at the single model elements.

In general there are four general types of powers:

- Input Power, e.g. in the External Torque element
- Stored Power Type A , e.g. in the Inertia element
- Stored Power Type B , e.g. in the Spring element
- Lost Power, e.g. in the Damper element

All SimulationX Elements in the libraries Linear Mechanics, Rotational Mechanics, Electronics, Electro-Mechanical Systems and Hydraulics calculated all there characteristic powers.

The following picture shows these powers in the different physical domains of SimulationX.

Power P	Input Power **PSrc**	Stored Power Type A **PStoreA**	Stored Power Type A **PStoreB**	Lost Power **PLoss**
Electronics	External Power **Pe** Voltage Source	Change of electrical field energy **Pelek** Capacitor	Change of magnetic field energy **Pmag** Inductor	Lost Power **Pl** Resistor
Elektro-Mechanics	-	-	Change of magnetic field energy **Pmag** DC-Motor	Lost Power **Pl** DC-Motor
Mechanics T	External Power **Pe** External Force	Change of kinetic energy **Pk** Mass	Change of potential energy **Pp** Spring	Lost Power **Pl** Damper
Mechanics R	External Power **Pe** External Torque	Change of kinetic energy **Pk**; Inertia	Change of potential energy **Pp** Spring	Lost Power **Pl** Damper
Hydraulics	External Power **Pext** Flow Source	Change of kinetic energy **Pk**; Line	Change of potential energy **Pp** Volume	

Figure 5: Powers in different physical domains of SimulationX

The Power Balance itself collects all powers of the basic elements in the model. Four new variables PSrc, PStoreA, PStoreB and PLoss are added to the model where the powers of that type are summed with corresponding balance equations. The corresponding transferred energies ESrc, EStoreA, EStoreB and ELoss are calculated by integration of the powers over time.

Comment	Name	Protocol
Power Loss	PLoss	☑
Energy Loss	ELoss	☑
Stored Power (Type A)	PStoreA	☑
Stored Energy (Type A)	EStoreA	☑
Stored Power (Type B)	PStoreB	☑
Stored Energy (Type B)	EStoreB	☑
Input Power	PSrc	☑
Input Energy	ESrc	☑

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// PowerBalance: Do not change manually!
PLoss=load.Pl+friction_motor.Pl+gear1.PLoss;
ELoss=integral(self.PLoss,0);
PStoreA=motor.Pk+inertia_load.Pk+gear1.PStoreA;
EStoreA=integral(self.PStoreA,0);
PStoreB=gear1.PStoreB;
EStoreB=integral(self.PStoreB,0);
PSrc=motor_torque.Pe+gear1.PSrc;
ESrc=integral(self.PSrc,0);
```

Figure 6: Power and energy variables and corresponding equations

In a “flat” model of a technical system one balance is sufficient to collect all occurring powers. In case of more complex systems, e.g. the reference machine, the complete model consists out of many submodel structures, i.e. the model has two or more model levels. In order to generate a complete Power Balance those models with substructures (Compounds) balances must be applied on every substructure level of the model, starting with the lowest level up to the complete model. By that all powers are taken into account in the overall Power Balance of the model. Variables for the power and energy sums are provided at every model substructure, so for example the power losses can be analyzed at a single model element (e.g. damper element), a substructure model (e.g. of a gear box) or the overall model (e.g. of the complete machine). The following picture visualizes this hierarchical Power Balance.

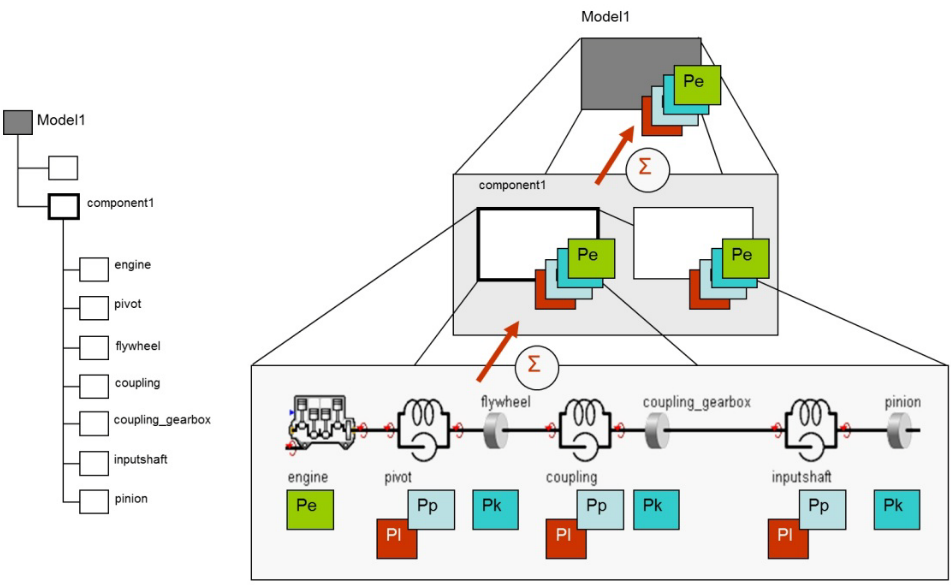

Figure 7: Hierarchical Power Balance in SimulationX

Beside that SimulationX provides with the Power Sensors special elements to measure the power flow in connections between model elements. They can be used in parallel in these model connections.

SimulationX supports also some useful diagram types for the visualization of the calculated powers and energies. There are two types of bar charts, a pie chart or a Sankey diagram.

Sankey diagrams are often used to visualize the energy flow or consumption in technical systems. The following picture shows a Sankey diagram of for a component in a drivetrain e.g. a gear stage. The input energy is fed into that by a motor. The biggest part of that energy is emitted to the further drivetrain. Minor parts are stored in the inertias or lost due to friction.

Figure 8: Sankey-Diagram in SimulationX

6. Summary

The objective of the research-project ENPROVI is the development of a prediction tool for the energy-consumption of mobile processing machines. The implementation will be based on the software SimulationX 3.5. In addition to the development of a methodical approach, various models for describing the process of mobile processing machinery are created. These models will be at disposal for future users.

The new tool “Power Balance” provides a useful possibility to analyze power flows and energy consumptions in SimulationX 3.5 models. All occurring powers are calculated at the basic model elements, collected by a hierarchical Power Balance and categorized and summed according to their four basic types. This should help the user to understand the power flows in the system and to optimize energy efficiency precisely. Beside that SimulationX 3.5 provides many possibilities to visualize the power and energy consumption of modeled systems, e.g. Sankey diagrams.