Mobile Systems – Markets, Industrial Needs and Technological Trends

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Abstract

This paper gives an overview of the current technologies and trends in the mobile machinery market. Several topics will be discussed including economical developments, market trends, state of the art, research being conducted and future directions. The mobile machinery market took a strong hit during the last couple of years due to the financial crisis the western world has experienced. However other markets were still growing, such as the Asian market. The north American and European market are focusing on cleaner and more energy efficient solutions, driven by the emission regulations. This has forced the industry to develop and adapt new solutions in hydraulic systems and components and engine technologies. Some of these technologies have shown their potential for quite some time but have never been incorporated or were only used in very specific applications.

A deeper focus will be taken on advancements in the system architectures and its subsystems such as valve technologies, displacement control, hydraulic transmissions and hybrids in mobile machinery. In conclusion a new joint research project "TEAM" is introduced, which is taking on the challenge to evaluate the newest advancements in the mobile machinery market and finding a way to utilize them in a demonstrator machine.

KEYWORDS: mobile machinery, technological trends, market situation, systems engineering, functional integration, valve systems, displacement control, travel drives, CVT, hybrid systems, TEAM

1. Global Markets for Mobile Machinery

After the year 2009, in which well established markets in Europe and North America have collapsed, global market volumes for mobile machinery have recovered and strongly developed within the last years. Besides the developed markets in the highly industrialized countries in Europe and North America, emerging markets in the so called BRIC (Brasil, Russia, India, China) countries have added substantial market potentials to the existing well established markets (**figure 1**).

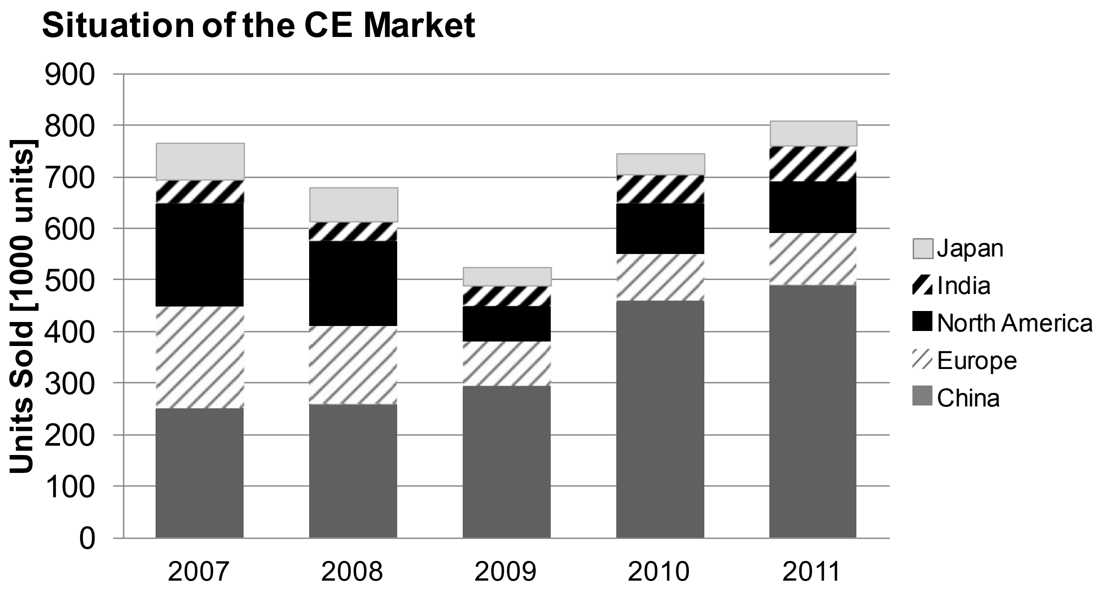

Figure 1: Construction equipment market 2007 – 2011 (Source: Off Highway Research)

From 2008 to 2010 the total market for hydraulic crawler excavators HEX (16 t – 90 t class) increased from 125.500 units to 156.000 units, where growth was mainly in BRIC markets (**figure 2**). Looking at the relation between total HEX market size and the size of the corresponding BRIC markets, we find a 65% market share of the BRIC markets considering the HEX product lines. Similar tendencies can be observed for wheel loaders, where BRIC markets are dominating total market growth.

Looking at some sales forecasts for the time period of 2011 to 2015 for China and India, Chinese construction equipment sales should increase by 16%, where the most significant growth rates are forecasted for crawler HEX (+41%) and a quite moderate growth rate for wheel loaders (2%). Corresponding sales forecast numbers for India show an enormous growth number of +56% for the whole range of construction equipment machinery. Again sales of crawler HEX are predicted to grow strongly by +133%, which will lead to 35.000 units to be sold in 2015.

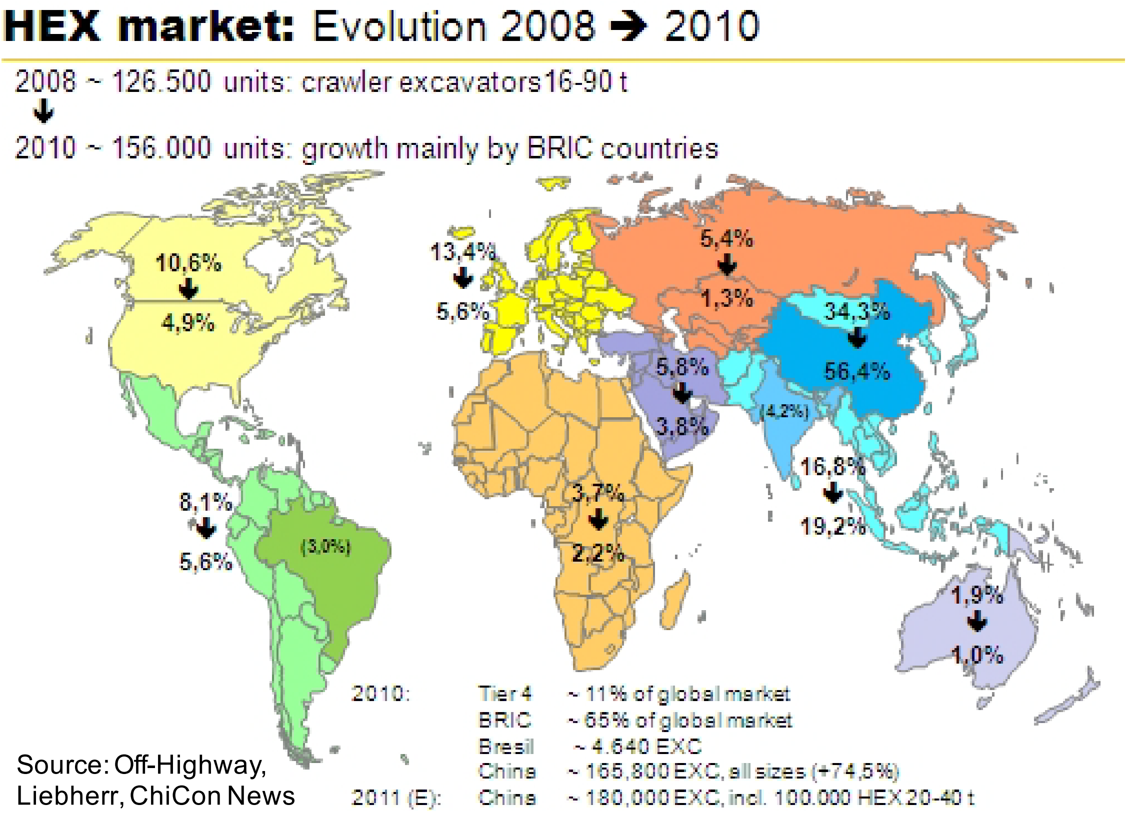

Figure 2: Hydraulic excavator market evolution 2008 – 2010

Significant sales increases are forecasted for wheel loaders, backhoe loaders and mobile cranes as well. For the developed markets in Europe and North America forecasts are showing only moderate growth rates within the next years.

2. Regulations and Product Technology

Based on different emission regulations to be fulfilled in different markets, engine technology and therefore product technology will be different for these markets. In Europe, where emission regulation based on the directive 97/68/EC: 2004/26/EC has to be respected and Stage IIIB certified engines have to be integrated in the final products since beginning of 2011 and 2012 respectively, new product generations are introduced now. For US and North America US/EPA/CARB emission regulations are obligatory and Tier 4 interim, corresponding to Stage IIIB in Europe, is introduced starting in 2011 and 2012 respectively.

Looking at the global market, it has to be considered, that for the example of *HEX* only 11% of the global market is subjected to Stage IIIB / Tier IV interim emission regulations and that 89% of the global market has lower emission standards, that means below the specified Stage IIIB/ Tier IV interim emission restrictions (**figure 3**).

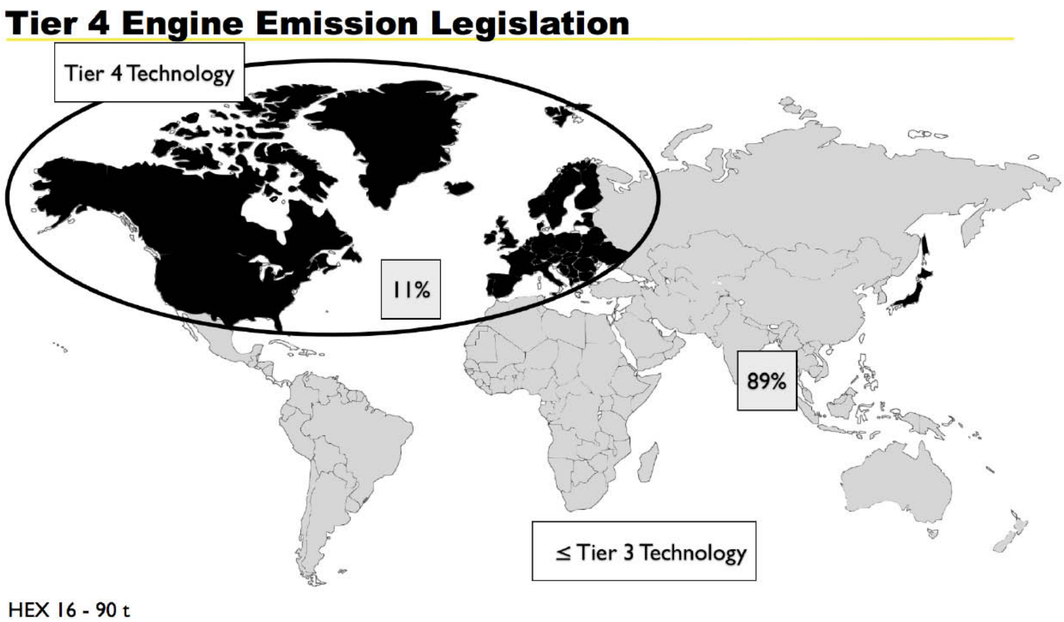

Figure 3: Emission levels and size of markets – here hydraulic excavators

Based on new engine technology for Stage IIIB/ Tier IV interim engines and exhaust systems necessary to guarantee low NO_x and particulate emissions, fuel quality has to fulfill minimum requirements for these engines. A schematic chart of available fuel qualities is given in the figure below (**figure 4**). As indicated in most parts of the global markets, except Europe, North America, Australia and Japan, fuel quality will not allow operating Stage IIIB/ Tier IV engines in construction equipment.

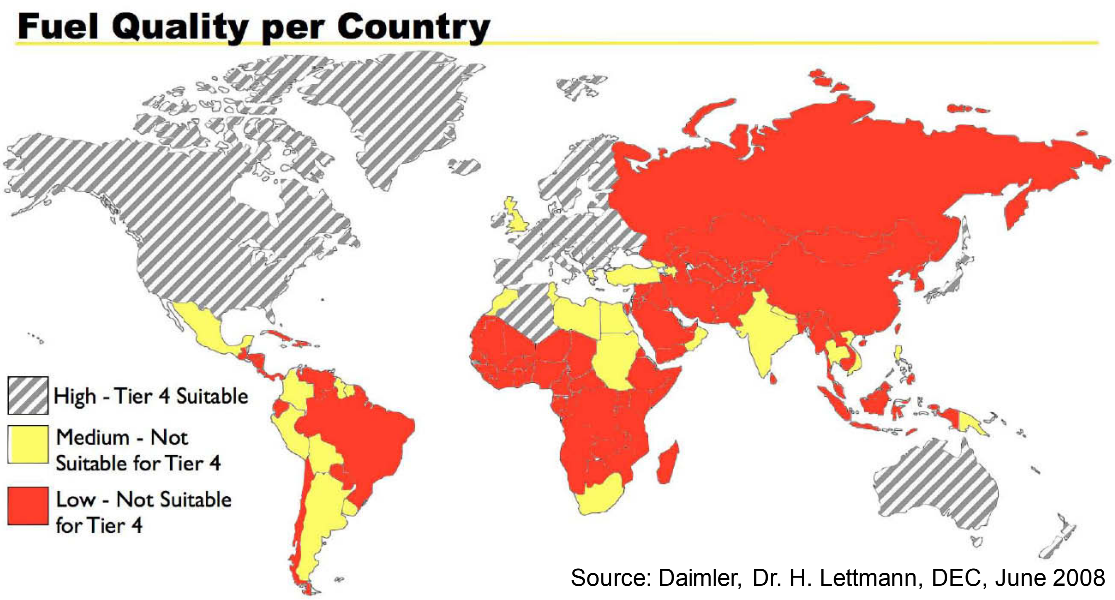

Figure 4: Fuel quality and resulting constraints on product application/sales

Consequently OEMs are forced to offer products with different engine technology levels. It has to be mentioned, that due to different product technology levels offered in different markets, corresponding price levels will be very different. Based on different product technology levels, market prices can vary by up to 50% looking at max. to min, prices for a given product class and different market areas.

Considering safety aspects, globalization has added a large variety of country/market specific regulations, leading to increasing product complexity for OEMs. With respect to safety aspects, OEMs are responsible to fulfill existing safety standards in highly regulated markets on one hand, but have to offer “state of the art” product safety in emerging markets on the other hand. So independent of legal specifications product safety strategies should be the same for developed and emerging markets. OEMs are obliged to offer safe products, independent of technology level.

Besides different legal regulations for different markets, product configurations will depend on different application of the end products and different experience levels of machine owners, drivers as well as service staff. Product management has to specify the positioning of a product in a specific market. Product positioning includes the definition of market specific configurations / options relevant for a given market and an appropriate field of application as well as the corresponding pricing in a market and a market specific field of competition. To avoid excessive increase of product variants, OEMs are forced to create product and technology platforms as a function of their market strategy.

3. Customer Needs and Technology Trends

Both, market differentiation as well as changing customer needs, will influence future product characteristics. New technologies available will further open new solutions for product configuration and application. The following main trends can be observed, which may be classified into three distinct categories:

- Increasing machine efficiency
- Increasing process efficiency
- Increasing operation efficiency

Increasing machine efficiency includes new technological concepts to optimize drive line systems in construction machinery (engine, hydraulics, transmissions).

The use of alternative energy sources, like electric motors (see **figure 5**) or hybrid systems is an important discussion, as it has been in the automotive industry in recent years. Electric power trains have been in research for the recent years /1/, /2/, however their role in the industry has only been as a technology carrier so far, for example in the bulldozer type D7E from Caterpillar (**figure 6**).

Figure 5: Electric Material Handler (Source: Liebherr)

Nevertheless it has to be pointed out, that hybrid systems may vary significantly for mobile construction machines, depending on the typical working cycle of a machine and the corresponding potential of energy savings/ increase of efficiency in these cycles. Higher system costs, as compared to existing conventional system solutions, for a hybrid system will only be accepted by the industry, if there will be a payback within a limited time of machine operation, e.g. a two years period.

Increasing process efficiency means selecting the right machine or combination of machines for a given application as well as using supporting technologies in these products, like “tool control” or “GPS” for process optimization.

It is in the interest of the customer as well as of the OEM to guarantee an optimized operating efficiency of their products. One important element for increasing operation efficiency is a professional training of the machine drivers. Besides a correct manipulation of the machine itself, a profound knowledge in application specific processes will be necessary to guarantee a competitive and correct result for a given work task.

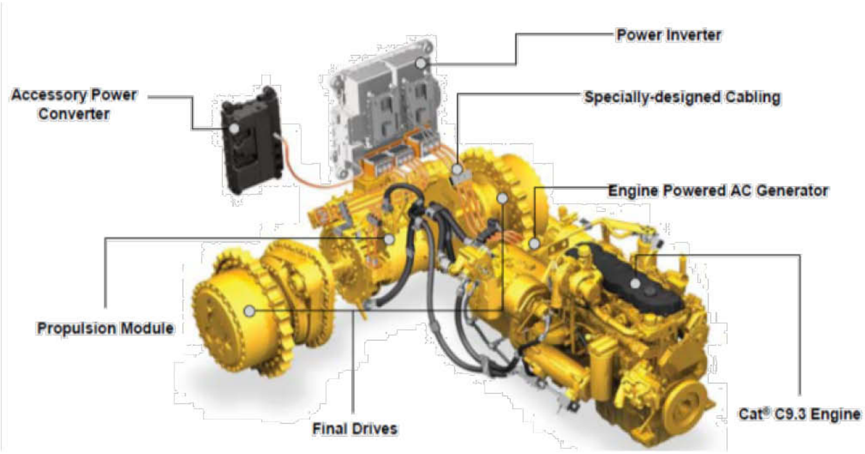

Figure 6: Electric Dozer CAT D7E (Source CAT)

A professional use of construction machines will not only increase the results of a working process but will in addition lead to increased machine life time, reduced down-time, lower fuel consumption and therefore lower life cycle costs for these machines. It is evident that investing into driver – training offers a high potential of cost savings for the machine owners.

4. Methodical System Integration

The complexity of drives and controls in mobile machines has significantly increased in recent years due to the growing amount of electronics. The application of modern electro-hydraulic drives has considerable potential to contribute to functionality and efficiency. The software is slowly taking over more and more parts of the control. Today's mobile drive systems are highly connected via bus communication (CAN, TTP) and consist of various interacting mechatronic devices. At the same time, particularly the non-functional requirements for mobile machines, such as exhaust, safety, environmental conditions, availability, robustness and total costs of ownership, are on the rise. The existing innovation potential can only be used if the complexity and the increasingly domain-overlapping characteristic within the system-developing-process remain controllable.

4.1. Advanced functionality

In recent years, several software-based functions were implemented into mobile machines. For example increased operation efficiency may be achieved by using sophisticated fleet-management systems in conjunction with "teleservices". Major machine manufacturers offer their own GPS-based system /3/. **Figure 7** shows Liebherr's telematic system LiDAT. These remote control systems are used for fleet disposition as well as for monitoring fuel consumption and productivity. Machine status can also be requested to check for necessary repair and maintenance. Work and load monitoring systems are increasingly integrated into the machine. For hydraulic excavators applied in demolition Liebherr has developed a „Liebherr Demolition Control (LDC)“ system to assist the driver in operating the machine safely. The inclination of the base machine is permanently measured and indicated to the driver. Sensors are used to measure the exact position of the long reach attachments and to calculate the appropriate work space. Safe operation of the machine is guaranteed by optical and acoustic warnings well before reaching positions. If necessary, hydraulic functions will be restricted to avoid unsafe machine operation. In addition to an audible warning, the work hydraulic of Liebherr’s telehandler is automatically slowed down before the machinery is in danger of tipping over. The control of the implement height and inclination are state of the art technology for graders, crawlers, compactors, and pavers /4/. Special geodesy-guide systems are used for 3D-orientation..

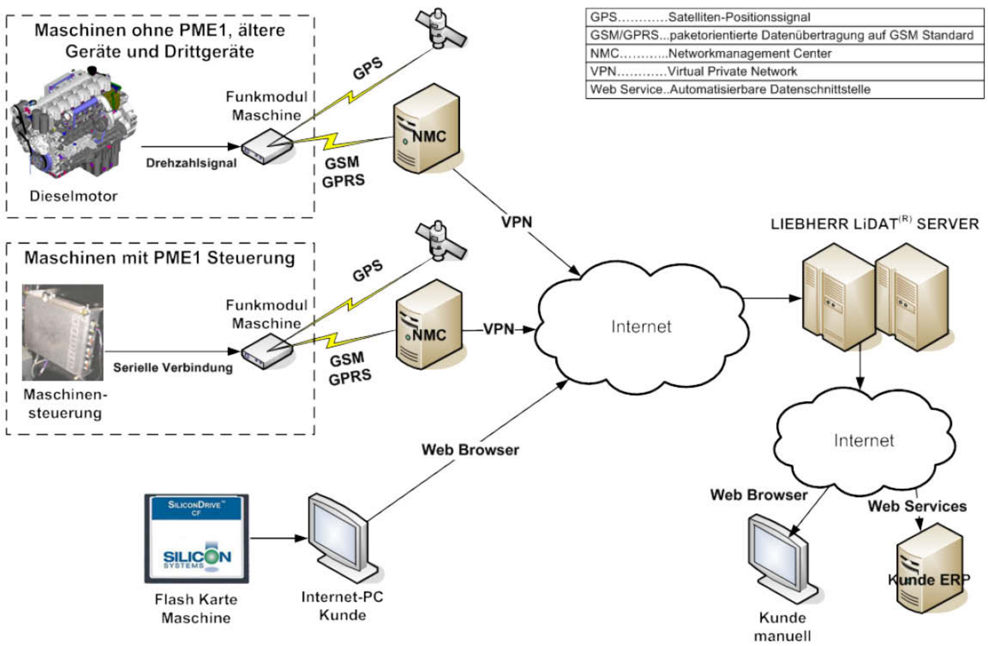

Figure 7: LiDAT – Machine Data Service (Source: Liebherr)

Additionally, rollers are equipped with an automatic compacter control /5/. Sensors monitor the actual compaction while the work parameters are adjusted simultaneously. Putzmeister’s *Ergonic Boom Control* is an innovative control which supports the user with operating the boom of a concrete pump /6/. The vertical and horizontal motion of the outlet hose is directly set via remote control without the need to consider in the complex kinematics. A limited work space can be programmed directly by tracing a path with the tip of the boom.

4.2. Model-based, domain-over-lapping system-developing process

To still be able to handle the complexity and heterogeneity of mobile systems in the future, a systematic system-developing process is necessary. It also guaranties long-term improvement of product quality and efficiency of work-flow. The so-called V-model is generally accepted as a quasi-standard in software development. The V-model was originally published as a standardized procedure for planning and developing civil and military IT systems in Germany. The current V-model version XT is a rigorous improvement and contains up-to-date methods and technologies /7/. The publication of the standard ISO 26262 in 2011 shows the relevance of the V-model /8/. The standard features the current state of technology in the automotive industry regarding functional safety of electric-electronic systems in motor vehicles. It was especially developed to avoid systematic errors during the entire development process. A life-cycle model based on the V-model was defined for this purpose.

The VDI guideline 2206 /9/ describes the domain over-lapping development process of mechatronic systems , which is accompanied by a model-based analysis, shown in **figure 8**.

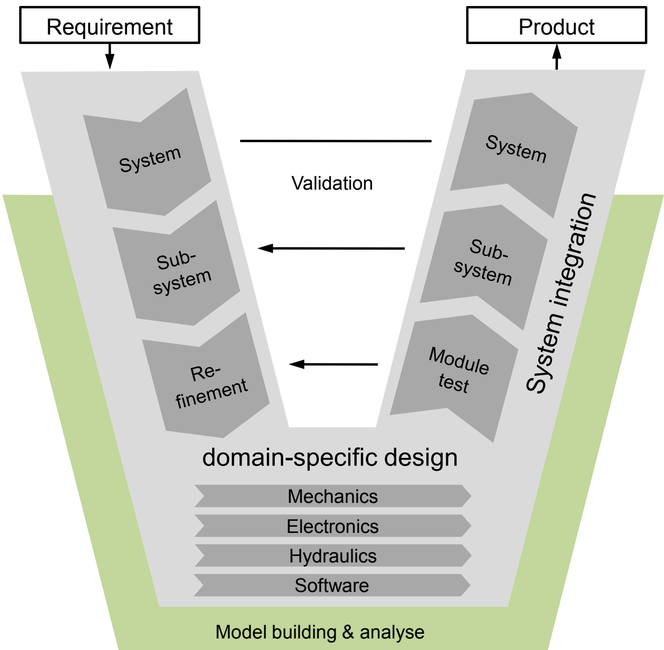

Figure 8: V-Model: development process of mechatronic systems /9/

The system development starts on the definition of the requirements. During the system design, a domain-over-lapping functional structure is developed. Following the top-down principle this structure is hierarchically subdivided into sub functions. At the lowest level, the domain-specific design level, the specific solutions are developed and implemented. The results of the single domains are combined into one system at the level of system integration. To guarantee a high quality for the integration, the levels of the V model's two branches are linked through module tests, integration tests and system tests. Errors and inconsistencies have to be detected and corrected as early as possible. The process ends with the final product.

The early virtual validation, so called "frontloading", ensures the system design far before the completion of the first prototype and significantly contributes to advanced product maturity. The system design based on modern simulation tools is standard in today's development departments. Product properties can be analyzed and screened early in the virtual development stage. Depending on the stage of development, different models exist: the requirements model, the structure model, the behavior model, etc. Ideally, the models are related on each other. The consequent pursuit opens up an enormous potential to improve product quality and efficiency of work-flow in industrial product development.

Very often the interdisciplinary communication between different disciplines (mechanical engineering, electrical engineering, computer science) complicates the design process. Reaching the full potential of fluid-mechatronic systems is only possible with a holistic analysis and optimization.

System modeling languages like SysML or ModelicaML solve this problem /10/. They are based on the object-oriented modeling language UML (Unified Modeling Language), which is well established in software development. The methods of all independent disciplines can be combined by means of SysML or ModelicaML. By using different abstraction levels (structure model, behavior model, requirements diagram, etc.) the general understanding of the system is sharpened. The system model is the source of all relevant information: specification, interfaces, system design, analysis and test planning. With its notations the modeling language reflects the engineering way of thinking. The languages should be used as a tool for a consistent, model-based system-development process in the spirit of the V-model. ModelicaML additionally features the creation of executable simulation models. This is the next step towards a consistent tool chain.

4.3. Functionality test and virtual start-up

Particularly during the phase of system integration, the system properties have to be constantly compared with the requirements. There are different ways to do it: purely virtual, partly virtual or real (model-, software-, hardware-in-the-loop, and prototype).

Hardware-in-the-loop (HiL) means that the real control device is tested with the compiled software on a real-time simulation model of the machine (**figure 9**). The technology is well established in the automotive industry /11/. In this manner, the product quality and efficiency of workflow are demonstrably improved. The machine functions, dangerous operation scenarios, error detection and diagnosis, the usability and the task management can be tested extensively. Fundamental programming errors are detected and corrected before the actual machine start-up. Consequently, it is possible to reduce time, costs and material usage for machine testing considerably.

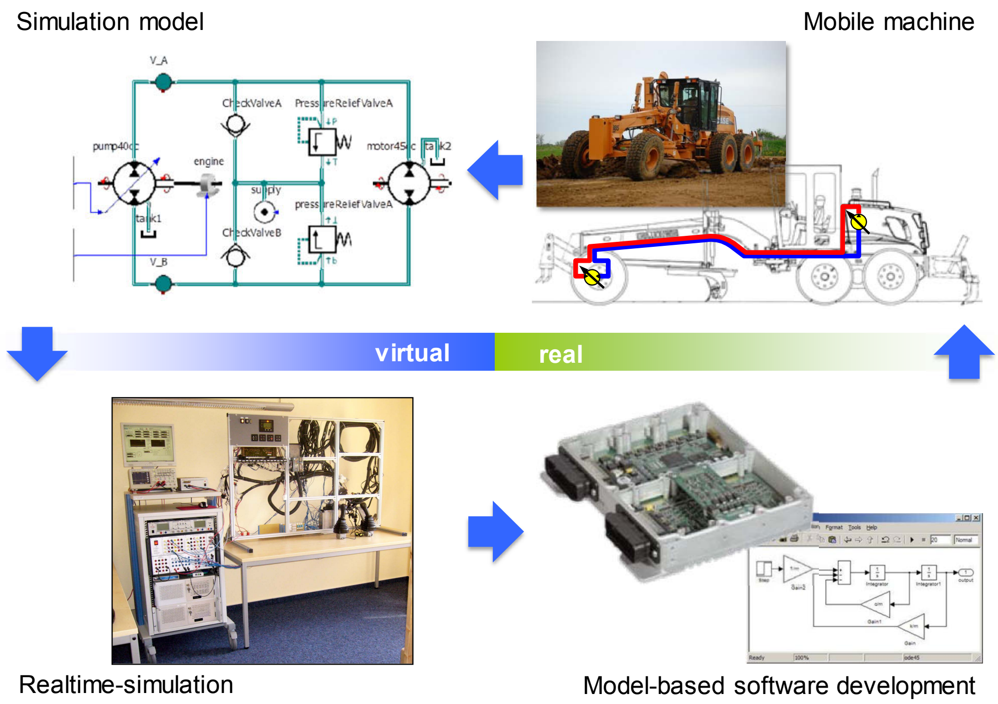

Figure 9: Virtual test with hardware-in-the-loop-simulation

The HiL method requires real-time simulation models of drive and control systems. The challenge is to reduce the model complexity without neglecting behavior-relevant system properties. Today, generating real-time simulation models is time and cost consuming. These costs contradict the desired efficiency increase. The availability of engineering capacity and expertise is a problem especially for small and medium-sized manufacturers of mobile machinery. Therefore, it would be useful to enable the existing simulation tools to support the test engineer in setting up real-time models.

5. High-Potential-Subsystems

5.1. New valve controlled hydraulic systems

State of the art. Currently there are different valve controlled architectures used in mobile machinery. Besides conventional throttle control in open center design, negative flow control, positive flow control and load sensing are being used as shown in **figure 10**. Common to all systems is a good response and dynamic behavior, but losses are recorded in partial load range especially. The "Linde Synchron Control LSC" and the "Load-Pressure-Independent-Flow-Sharing LUDV" of Bosch Rexroth are two representatives, which have been established in the market. The increasing usage of electronic control, led and still leads to an intensified development of electro-hydraulic (EH) systems for the machine implements.

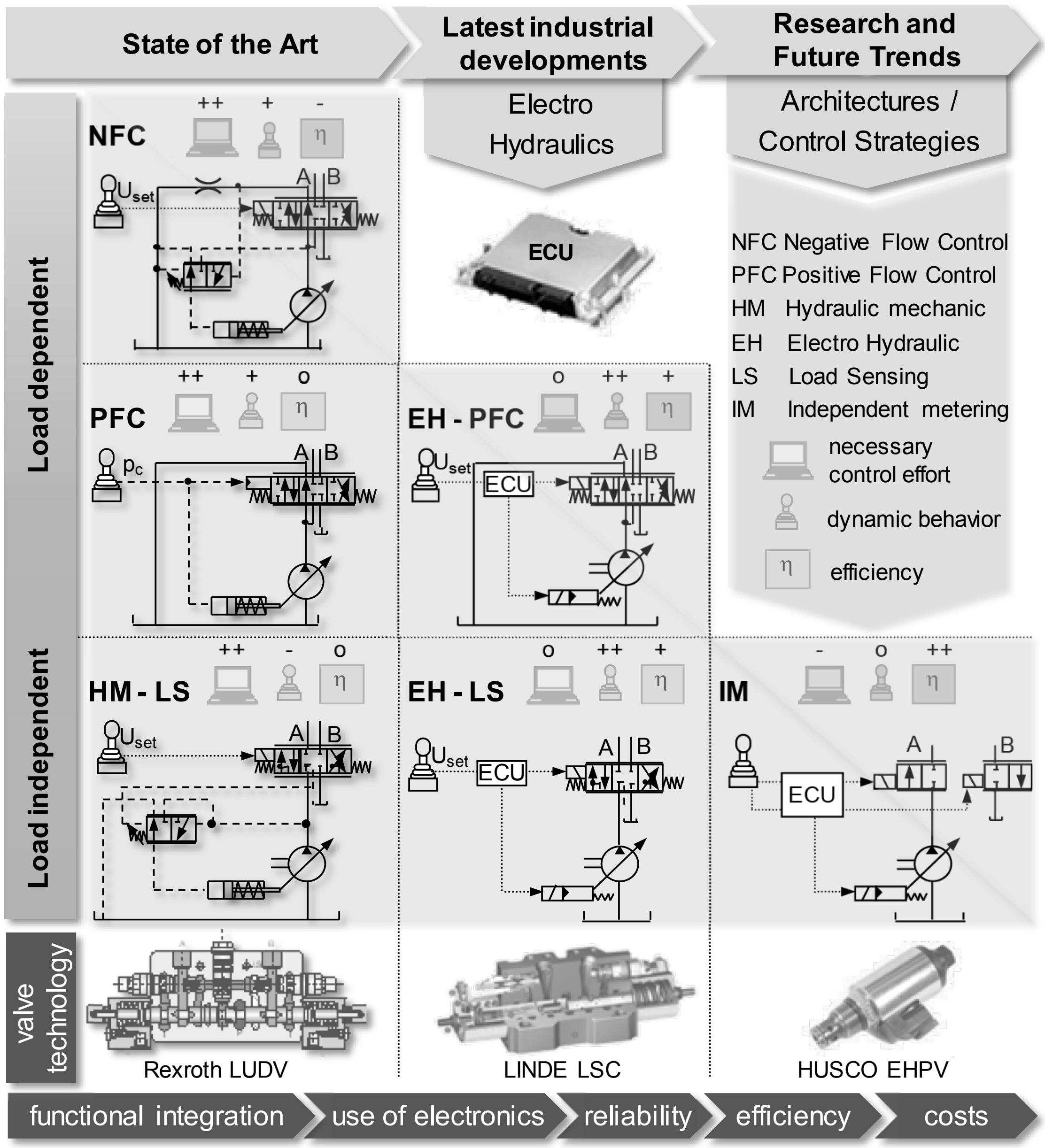

Figure 10: Principles and assessment of working hydraulics

In that way several OEM have developed their own systems. Examples here are the multi-circuit Pump Management System PMS by CNH formerly Orenstein & Koppel /12/ and the Litronic-system by Liebherr /13/. Both systems detect the operator input signals. The electronic controller adjusts the pump displacement and the resulting volume flow, meeting the load requirements. Moreover, the PMS system offers the possibility to optimize work processes and to monitor the operating status of the machine by using the electronic board control system /12/.

Industrial Developments – Architectures. An extension of the positive-flow-control system (PFC) with pressure sensors combined with an electro-hydraulic control of the pump is implemented within the "Virtual Bleed Off VBO" system by Bosch Rexroth. Through additional integration of engine management in the control unit and the separation of hydraulic circuits often operated in parallel, an energy-efficient solution is obtained /14/. Such advanced system technology is used in the new generation of Liebherr crawler excavators. The integrated system consists of a "positive control 2 circuit hydraulic system", a newly developed electronic control system (master, I/O – modules) with new software as well as an integrated engine control. Fuel efficiency was increased by up to 20 % compared to the previous generation of products. To enable the regeneration of stored energy, many companies like Caterpillar and Liebherr have begun using regeneration circuits to save energy during the boom-lowering and stick-in operations /15/, /16/.

The attempt of a systematical improvement of the dynamics and robustness of systems led to intensified research on advanced control concepts. Among other concepts multi-variable control /17/, fuzzy-control /18/ or neural networks /19/ have been investigated. Beside the system complexity, the increasing requirements regarding machine safety and costs have to be taken into account.

The "Electro-hydraulic Flow Matching EFM" /20/, /21/ represents a specific Closed-Center architecture, which is consistent with the strict use of separate electronic control of valves and pump as well as Open-Center EH-PFC. The efficiency advantage is achieved by precise control of the pump flow, following the operator request, compared to the flow reserve of conventional CC-systems. A decisive advantage of this system is the improved static and dynamic behavior despite of the absence of sensors and higher control strategies.

Industrial Developments – Valve Technology. To take full advantage of digital signal processing on valve level, there is a variety of company-specific solutions for accurate and efficient mobile valves /22/, /23/, /24/, /25/. In addition to integrated basic LS functions, there is a large amount of additional functionalities, such as position-controlled main spools, efficient and highly accurate pilot stages, integrated individual pressure compensators as well as on-board-electronics (OBE) with bus interfaces. The electronics in particular provide a quick and easy manipulation of the spool- and flow characteristics at the software level. In addition a reduction of cabling and commissioning work is possible. Another important aspect is the opportunity of implementing safety and diagnostic functions into the OBE.

The focus in the field of actuating mechanisms of valves is especially the dynamic behavior and accuracy. The so-called “Smart Actuator” by Sonceboz for example, is an interesting alternative to conventional solutions. The elimination of the hydraulic pilot circuit and the associated losses, in combination with a capable OBE makes it to an efficient and intelligent valve subsystem /26/.

A further topic is the efficient manufacturing process of the manifolds. The layer-brazing-technology introduced by Linde shows improved, flow-optimized duct layout compared to conventional drilled manifolds /27/.

Research and Future Trends. Current valve controlled architectures are characterized by associated control edges. Many researches and patents refer to this constraint and try to resolve the mechanical connection in order to gain benefit of the additional degree of freedom. The expected benefits such as reducing the losses at the tank edges, free choice of the pressure level and the use of stored energy potentials have to be weighed against the additional costs incurred due to the components. In addition to various valve designs and concepts there are several different types of system approaches (/28/, /29/, /30/, /31/). In particular, solutions with 2/2-way valves have been the subject of recent research. These valves are designed very simple, thus cost efficient and can be manufactured without leakage in seat type design. A first applications are known from HUSCO /32/. Erickson and Palmberg introduced a system, which can be operated without the use of pressure sensors /33/. The stability of the control strategies in 2/2-way systems is a major topic in research by Linjama and Vilenius /34/. In general the component effort and the complex structure are some of the reasons why systems with independent metering edges still do not play a significant role in mobile machinery. There is a lack of basic investigations on this technology, especially concerning the difficult controllability. That is why the Institute of fluid power at the Technical University of Dresden addresses this topic in current research projects.

The philosophy of Digital hydraulics found its way into the research of hydraulic drive technology some years ago. Out of the variety of digital concepts fast switching valves show an interesting potential. These valves are controlled by a pulse-width or pulse-frequency-modulation and thus allow the setting of an average flow rate /35/. In order to provide higher flow rates several valves are proposed in parallel arrangement. The advantages e.g. higher efficiency, improved programmability have to be compared to controllability, reliability and component effort. The digital approach is targeting directly on the valve technology. Ideally these valves shall become a mass production part with low unit costs and thus replace expensive proportional and servo valves. The obvious disadvantages such as the expected pulsations and the resolution limit are development priorities /36/.

5.2. Displacement Control (DC)

The power losses inherent to valve control are a major source of power losses in today's hydraulic systems. Several alternative concepts have been proposed in recent years to replace valves with other means of flow control. There are three basic concepts: variable displacement pumps, variable speed pumps, and transformers that vary flow rate and pressure.

Innas has developed hydraulic components in form of hydraulic transformers. They are designed to convert hydraulic power between pressure and flow rate. An innovative transformer design is based on a single hydrostatic rotating unit with three ports. Although an ideal transformer would be an ideal solution, but a transformer design with high efficiency, high control bandwidth and low noise at an acceptable cost has not yet been achieved /37/. Another novel design based on a linear actuator with a discretely variable piston area has been proposed, but is still far from practical use /38/.

Displacement control using a constant displacement pump and a variable speed motor has been used in aviation and in stationary hydraulics, for example in injection molding for decades. Its advantages are lower losses while holding loads, easier controllability and low idle losses. However this concept (also known as electro-hydrostatic actuation or EHA) has recently been tried apply to other mobile equipment in form of electric hybrid configurations (/39/, /40/, /41/). Due to a requirement of an electric motor and the necessity of having electric power available on the machine, this technology has not yet been able to enter the mobile machinery market, except for some technology carriers.

Displacement control by means of variable pumps is currently the strongest candidate to challenge conventional valve-controlled hydraulic systems. Since the first displacement controlled O&K wheel loader prototype was introduced as part of an EU-research project back in 2003 /42/, /43/, and showed tremendous energy improvements some additional mobile machines have been converted to DC by the MAHA fluid power lab in Purdue, USA. In 2007 a Bobcat skid steer unit equipped with DC and active vibration damping showed 20 % fuel improvement /44/. In 2008 a mini-excavator (**Figure 11**) demonstrated 50 % energy saving by introducing DC /45/. Challenges for the variable pump DC are the higher costs due to a higher number of pumps required, and the small selection of high dynamic pumps capable for DC.

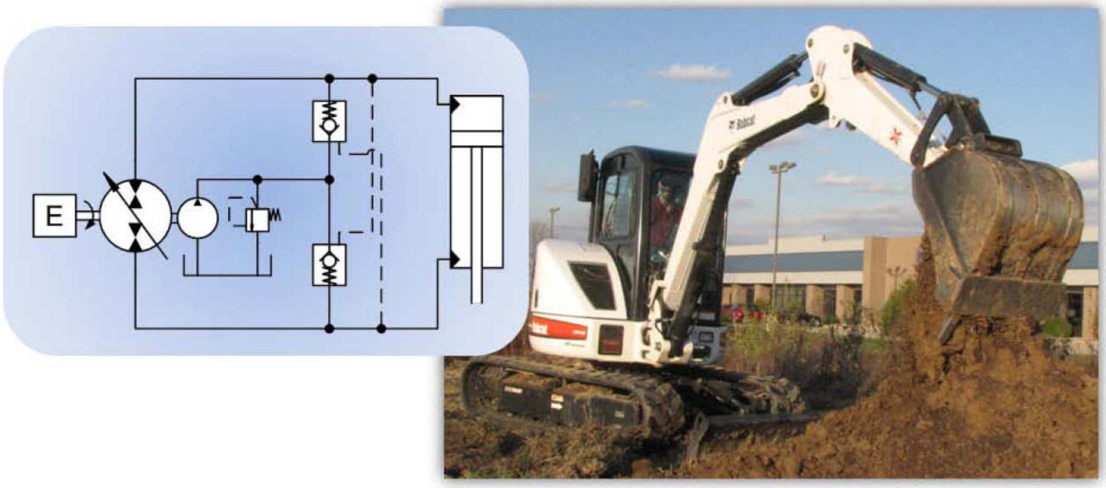

Figure 11: Displacement Controlled Excavator (Source: MAHA Fluid Power Lab)

Open circuit DC control systems as an alternative have been proposed by the university of Linköping in 2006 /46/. DC pumps in closed circuits have to be sized larger than open circuit pumps in a comparable valve-controlled system due to the unequal fluid volumes of the single-rod cylinder. This unequal flow paradigm was solved using directional flow valves. This solution has the advantage of small sized units, but requires a more complicated control law /47/. Open-circuit DC actuators were demonstrated on a wheel loader /48/. However if smaller pump units are used, the potential for energy recover is decreased.

Displacement Control does not only save energy by eliminating throttle losses, but in addition is opens the door for other promising technology such as hybrid solutions and engine management due to its ability to operate in all four quadrants.

5.3. CVT

The drive train is the main function besides the attachment system in many machines and vehicles. Its primary function is to ensure a comfortable ride combined with proper control of the vehicle, but simultaneously ensure to meet the high demands regarding cost, robustness, power, noise, energy efficiency and available space. In mobile machines there are two widely used types of torque converting transmissions: The hydrodynamic and the hydrostatic.

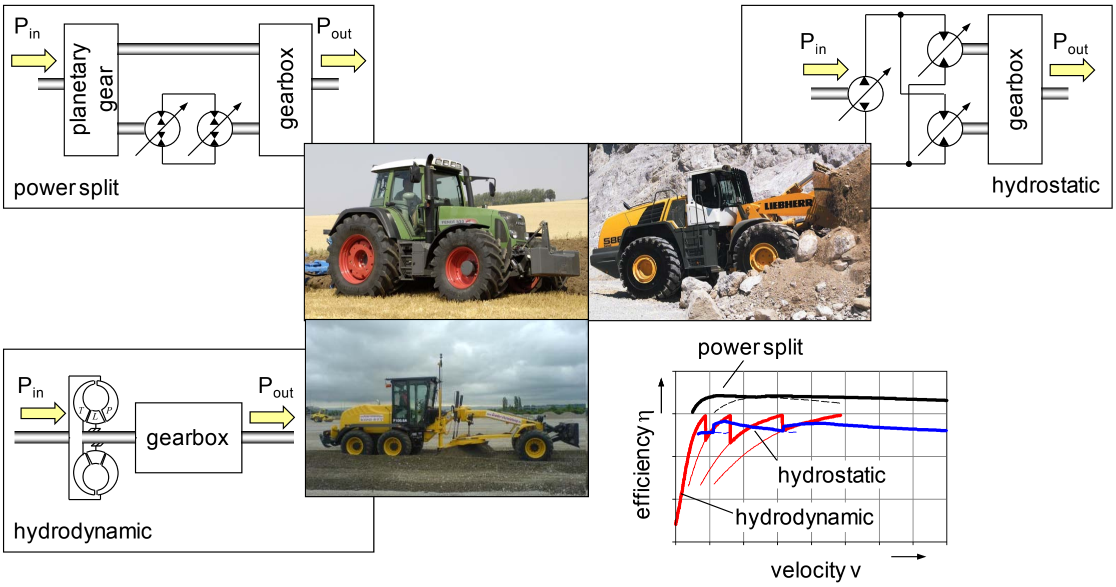

Figure 12: Typical transmissions for mobile machinery

Driven by rising fuel costs, federal regulations, and competition the energy efficiency became the main focus in the advancements and new developments in this technology. Multiphase converters and lockup clutches enable hydrodynamic drive trains to lower their energy consumption even further. Current examples of this technology can be found in VOITH /49/ or ZF /50/ transmissions. VOLVO introduced an optimized power train control strategy for wheel loaders at the “Bauma 2010” exhibition. They declare an automatic control via the brake instead of the hydrodynamic converter /51/.

Machine and component manufacturers offer many solutions that further increase the efficiency of hydrostatic power trains. Along the lines of the hydrodynamic transmission there are extensive solutions with switchable through-shafts (lockup clutches), economical powertrains with several motors /52/, /53/ (**figure 13a**) and highly efficient displacement units /54/ (figure 13b).

The company Linde increase the use of hydrostatic powertrains with its “p+” series (figure 13c). The corner power of the drive train was significantly increased by raising the operating pressure to 500 bar and allowing peak pressures of up to 580 bar /55/.

Besides hydrostatic and hydrodynamic powertrains, there is another promising approach in hydrostatic-mechanical power split transmission. These transmissions consist of a hydrostatic and a mechanical path and usually connected via planetary gear systems. In the last 15 years, these power-split systems are successfully established in the agricultural sector, specifically in tractors.

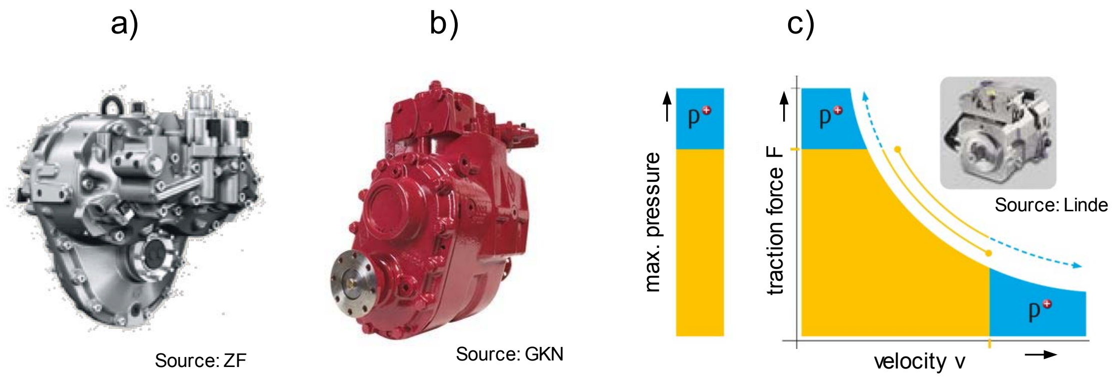

Figure 13: Hydrostatic transmissions examples

The use of these power-split transmissions in mobile machinery represents a new technical challenge. There are already some manufacturers that offer solutions in this sector, mainly for wheelloaders. Wheelloaders have several distinct driving modes, each with their own set of demands. The companies DANA, REXROTH Transmission Systems (**figure 14b**) and VDS Transmissions (figure 14c) offer systems with pure hydrostatic reverse operation and power-split forward operation /56/, /57/.

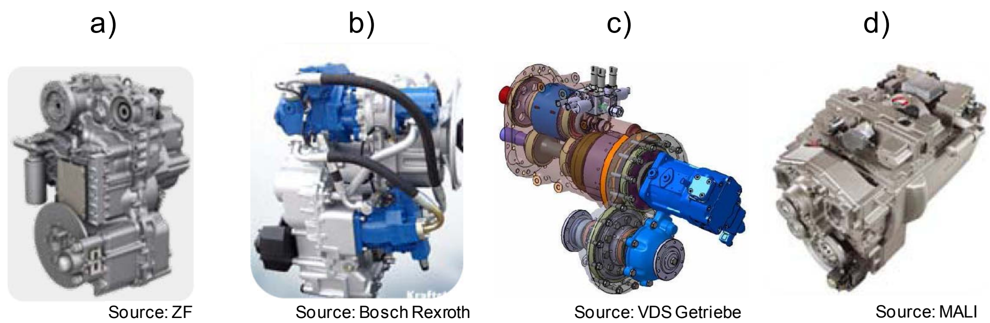

Figure 14: Power-split transmission examples

Compared to these solutions the company ZF presented a new kind of power-split for wheel loaders at the “Bauma 2010” exhibition /58/ (figure 14a). This power-split has two or three modes of operation in each reverse and forward mode, which depend on the power output of the machine. The machine is switched into reverse using a reversing gear. The displacement units are arranged in a dual yoke formation described by GÖLLNER in /59/. In comparison to the conventional arrangement, the dual yoke concept doesn’t need any high pressure swivel joint and related sealings. In addition there are further energy improvements due to the lower line losses in the flow optimized oil channels.

An additional gain from a power split transmission is the ability to manage the combustion engine. The proper adjustment between the load level of the machine, the gear ratios and the operating point of the combustion engine has a significant impact on the fuel consumption. In hydrostatic transmissions the continuously variable gear ratio can be defined for each operating condition and therefore offers ideal conditions for optimized energy management of the power-train. Using the wheelloader as an example, energy savings from 5 to 10 % are expected in certain operating modes alone by using proper engine management and CVT drives /60/ (**figure 15**). This saving potential can be achieved, especially using modern electronic control methods.

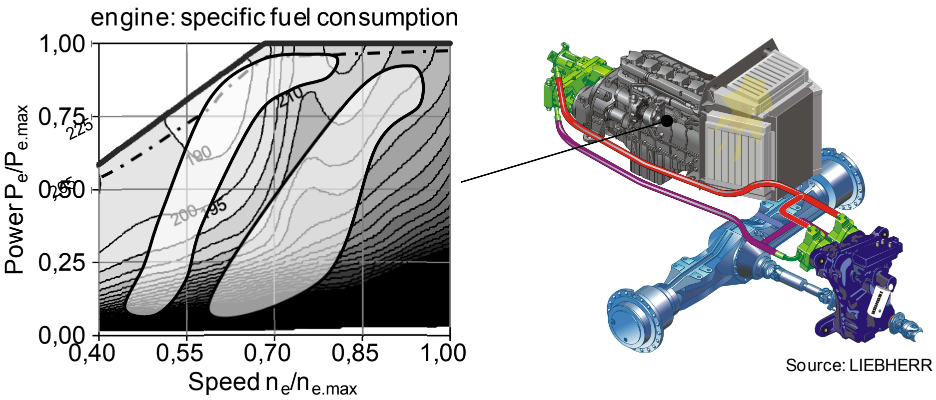

Figure 15: Fuel saving by an improved engine operation mode.

Advanced control strategies also allow the implementation of additional functions. Already today some manufacturers offer several add-on features such as the traction-force limiter /61/ or a reduction of the travel speed depending on the steering angle.

5.4. Hybrid Systems

As pointed out in chapter 3, many OEMs are currently developing hybrid systems for their machines. The most common reason for the use of hybrid drive train structures is the attempt to increase the machine's energy and fuel efficiency.

However, there are diverse other reasons for their implementation:

- Smoothing of the engine load, resulting in reduced exhaust emissions
- Increase of the machine performance (boost function)
- Maintaining the machine performance while using a smaller engine (boost + down-sizing)
- Reduction of component wear (brake pads etc.)
- (temporarily) emission-free machine operation, e.g. for indoor use

As diverse as the motivations for the use of these systems are the options of energy feed into the storage device:

- Recuperation of kinetic energy (from travel or swing drives)
- Recuperation of potential energy (from implement hydraulics and winch drives)
- Absorption of excess power from the engine at idle and partial load operation
- Feeding from external sources (plug-in hybrids)

Due to the multitude of reasons for hybridization and requirements regarding different machines various solutions have been developed. In the last years, electrical as well hydraulic hybrid systems were proposed, both in parallel, series and power-split structures.

A “winning technology” cannot yet be determined. Different hybrid concepts are promoted for different subsystems and product families (excavators, wheel loaders, dozers, etc.) but market acceptance of such products is still quite limited. Only a few concepts have reached series production readiness so far, the majority is still in a proof-of-concept or demonstrator phase /62/. This is mainly because of the challenges that have to be addressed when implementing hybrid systems:

- The complexity of machine control is increased significantly, which leads to the necessity of well-trained engineering and service personnel.
- Hybrid systems may cause additional requirements regarding machine safety
- The integration of the hybrid system’s components leads to packaging and weight issues
- The component lifetime, especially of electric systems, often does not yet meet the requirements

Systems for the recuperation of kinetic energy. Kinetic energy can be recuperated most effectively during fast and active deceleration of high rotational and translatory inertias. This is the case for heavy vehicles with distinctive stop-and-go operation, e.g. refuse collection and delivery vehicles as well as the swing movement of the upper carriage of an excavator. To use this energy, otherwise wasted in heat, different solutions have been developed.

Common approaches are parallel hybrid systems like Eaton’s Hydraulic Launch Assist (HLA) /63/ and Bosch Rexroth’s Hydrostatic Regenerative Braking System (HRB) /64/, shown in **figure 16**. They are used in addition to the vehicle’s conventional drive train, which simplifies the integration into the existing machine. Today both systems are commercially available for refuse collection vehicles. Field tests show fuel consumption reduction of more than 20 % and a significant reduction of brake wear /63/, /64/.

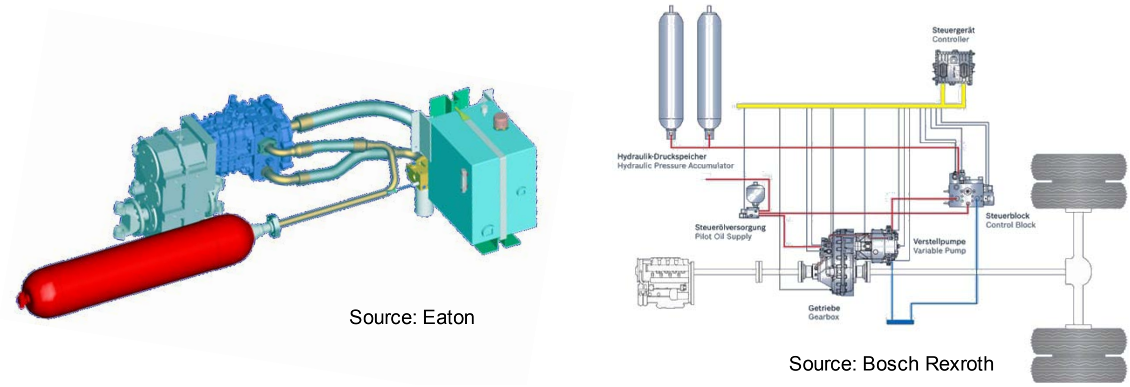

Figure 16: Hydraulic parallel hybrids for travel drives: Eaton's "HLA" /63/ (left) and Bosch Rexroth's "HRB" /64/ (right)

By replacing the conventional drive train, series hybrids do not only offer the possibility of energy recuperation but also the optimization of the engine's operating point. Parker's hydraulic "Runwise" system designed for refuse collection and delivery vehicles as well as for container handling vehicles in ports, shows measured fuel consumption reduction of more than 15 % /65/. Electric series hybrid systems are currently being developed for automated guided vehicles (AGVs) used in ports for container handling /66/.

For energy recuperation from the swing drive of excavators, Komatsu developed an electric swing drive with capacitors for storing the excess energy during braking. The commercially available machine is said to save 25 % fuel compared to the equivalent standard machine. However, the high cost of the system leads to a long payback period which reduces the attractiveness for machine users.

Systems for the recuperation of potential energy. Mobile machines like cranes, excavators and forklifts are characterized by duty cycles with distinctive periods of lowering and lifting loads. Recuperation of potential energy during lowering the load cannot only increase the machine's fuel efficiency but also reduce exhaust emissions and improve machine performance. As diverse as the requirements are the energy storage solutions for the different machines.

For dockside cranes, productivity and fuel efficiency play a major role because of the increasing requirements regarding handling capacity and operating costs. With the "Pactronic" system, Liebherr has developed a hybrid winch drive system for material handling machinery /67/, which is presented on this conference.

Hydraulic excavators offer potential for energy recuperation from their implement hydraulics. **Figure 17** shows a concept for capturing energy during boom lowering. The boom cylinders are driven by two hydraulic displacement units, one connected to an accumulator. Thus, the energy captured during lowering the load can be reused. By using a secondary-controlled swing drive, the recuperation potential can be extended /68/.

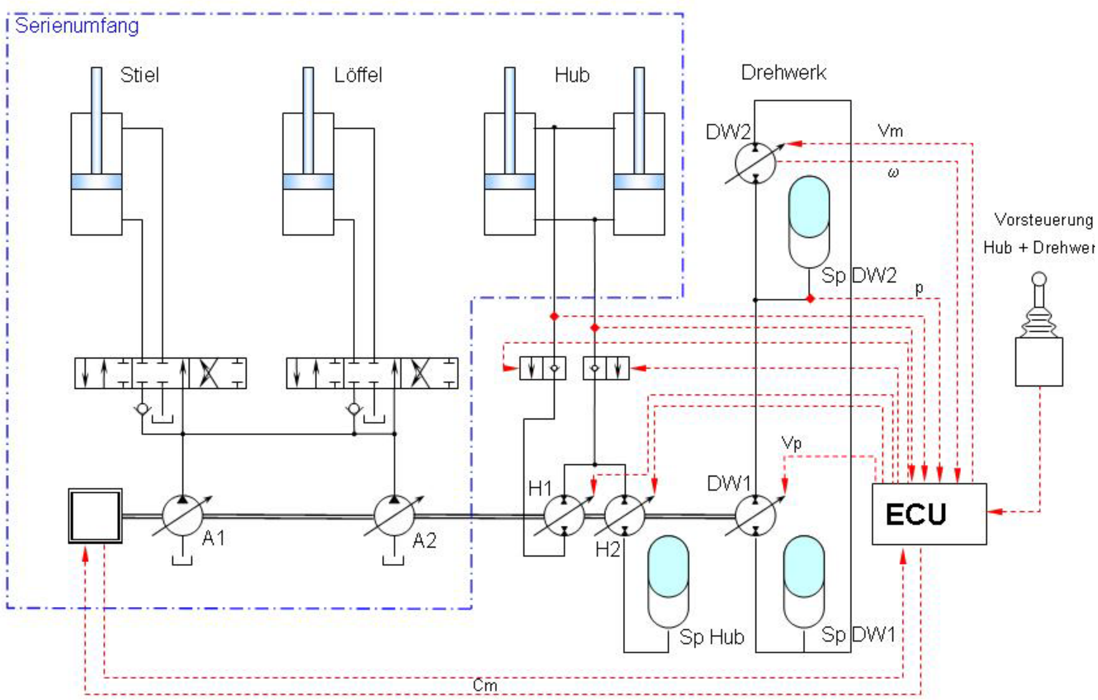

Figure 17: Hydraulic hybrid system for an excavator – recuperation of swing and attachment energy [Source: LIEBHERR]

Forklift trucks also have duty cycles suitable for recuperation. A large number of these machines are equipped with electric drives for indoor operation. To recover potential energy from the lift frame's hydraulic drive, a system has been developed by Jungheinrich and Weber Hydraulik /69/. Instead of throttling the cylinder's backflow to the tank, the valve block redirects the oil back to the pump. A frequency-controlled motor stores the energy in the machine's battery for later use. Thus, consumption reductions of more than 30 % are possible.

Hybrid systems for the support of the diesel engine. Besides the described systems specialized on certain subsystems solutions have been developed to support the diesel engine independent of the type of load.

The Hydraulic Flywheel (HFW) technology developed by Bosch Rexroth can absorb energy from the implement hydraulics as well as from a hydrostatic travel drive /70/.

The stored energy can be used either for increasing the machine's productivity through boosting or for consumption reduction by power smoothing of the diesel engine. The system is controlled based on the engine speed.

A similar approach is taken by Sauer Danfoss with its Hydraulic Power Boost (HPB). The system is designed for cost-sensitive applications like compact loaders with nominal engine power output close to 56 kW /70/. By modifying the existing variable speed fan drive the machine can be provided with a short-term surplus of power out of a hydropneumatic accumulator. Thus, the use of an engine smaller than 56 kW becomes possible, resulting in less necessary effort for exhaust gas treatment. **Figure 18** shows the principal layout of the system. The decision when to charge and discharge the accumulator is done based on the engine speed.

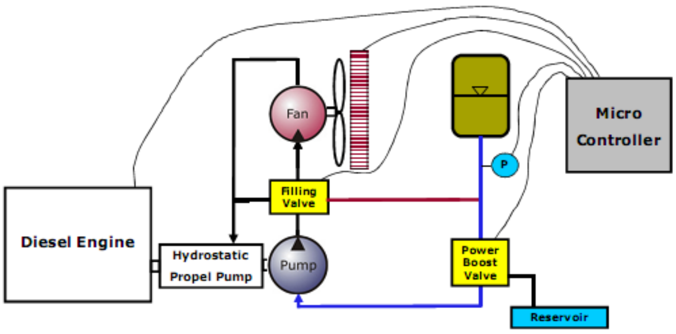

Figure 18: "Hybrid Power Boost" system for cost sensitive applications /71/

Another road is taken by Kawasaki with its Hybrid Torque Converter (HYTC) for wheel loaders presented at the ConExpo 2011 /72/. Instead of a conventional torque converter, a planetary gear connected to the engine's crankshaft and an electric motor are used. By changing the electric motor's speed, the power output to the conventional drive train can be controlled. The setup can be used for energy recuperation into a capacitor during braking or lowering a load.

The companies Heinzmann, ZF and Volvo have developed systems with an electric motor connected directly to the engine for different applications. Small and large wheel loaders as well as multifunctional hydraulic excavators have been used to demonstrate the functionality of the approach.

Holistic power management for further improvement. All before mentioned concepts are designed to support specific subsystems and are able to improve the machine performance and efficiency. The integration of all subsystems into a holistic power management of the machine offers further potential for improvement. To manage the power flow between the engine, the storage and the different loads, a systematic cross link of the subsystems and sophisticated control algorithms are required. The holistic power management and control strategy has to cover all these functions and subsystems without changing operating characteristic noticeable to the machine operator.

6. Conclusion and Outlook

The financial crisis in 2009 has caused substantial losses of market volume in the industrialized countries in Europe and Northern America for manufacturers of mobile equipment. Emerging markets in Asia and Southern America were able to compensate for the declining sales numbers but the market structure changed persistently. OEMs have to offer technologically advanced machinery for the highly regulated markets of the western world as well as robust and well-prized machines for the emerging countries.

The legislation on exhaust and CO_2 emissions, noise and machine safety in the western countries require high development efforts of the machine manufacturers as well as the suppliers of subsystems and components. Additionally, operators and machine owners demand for versatile, performing and energy efficient machines that are easy to operate.

The previous sections of this paper have shown the approaches for the different subsystems of mobile machinery to fulfill the statutory requirements, the regionally different market requirements and customer needs. The increased use of electronics is a key factor to develop sophisticated and cost-efficient solutions. Due to the increased use of electronic controllers and drive components the OEMs have to develop their core competence increasingly in the system integration process. Well trained engineering and service personnel is necessary to ensure products' success and market acceptance.

The high potential subsystem solutions discussed in this paper all have the capability of improving the machine's performance and efficiency. Research investigations have shown that the latest technologies in energy management strategies have the potential of a 20 to 40 % reduction in energy usage and emissions. Many of these solutions already passed their conceptual stage. However a consequent combination of these new technologies such as power split drives, hybrid configurations, and displacement control has not been tested or investigated.

High speed electric drives or engines that are designed to run at one optimized operating condition are new developments from the automotive field but their potential and their application in the mobile machinery sector has yet to be investigated.

These and more challenges will be addressed by a joint research project called "TEAM" aided by the federal ministry of education and research (BMBF). TEAM consists of 20 industry partners and 5 academic research teams, who will be collaborating to further advance current technologies and develop solutions to combine them. The goal of this joint research project is the development, test and evaluation of innovative methods and power train technologies to further increase energy efficiency of mobile machinery. In order to reach this goal the consortium created several workgroups that focus on specific topics and work closely together.

The topic "Evaluation of Energy Efficiency" focuses on the development of methods and instruments that can be used to assess the energy efficiency of power trains and can therefore form a base for a scientific evaluation of the energy consumption of mobile machinery. Besides investigating the machine performance under defined operating conditions, further aspects influencing machine efficiency, such as the work task and the operator behavior, will be analyzed (see **figure 19)**.

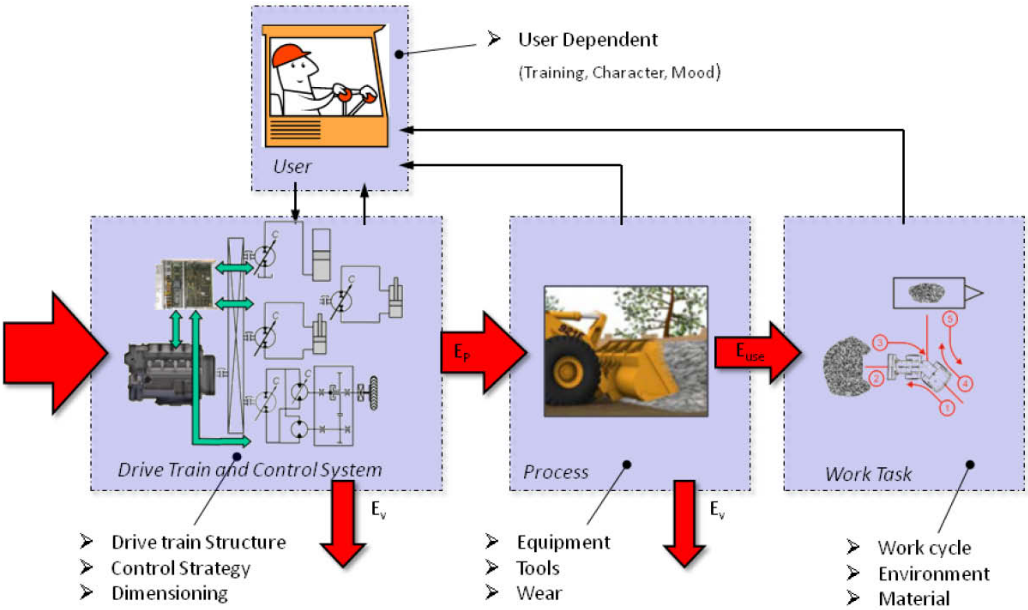

Figure 19: Main factors for energy efficiency

The workgroup "Process Energy" dedicates itself with the development of prediction tools for early calculations and evaluations of the energy usage due to the working cycle, for example the interaction between shovel and ground on a mobile machinery.

Another workgroup is focused on the “Single Point Engine”. The goal is to develop an engine that has a narrow optimized working range that can work with other substructures such as power split drives and hybrid functions. The objective is to significantly decrease CO_2 emissions without increasing the cost or sacrifice power.

“Electric High Speed Drives” are another workgroup that deals with the implementation and development of compact high speed electric motors that in the mobile machinery sector by making them more versatile and robust.

The largest workgroup is titled “Green Wheel Loader”. The goal is to develop and test drive trains and control strategies that inherit many of the previously mentioned technologies and combine them without reducing the functionality and user friendliness. Each sub function (working hydraulics, drive train, energy storage and combustion engine) will be evaluated with consideration to today’s technology in industry. The most favorite solutions will be merged into a 200 kW wheel loader demonstrator with a superordinated control strategy. The interaction between the subsystems will be given high priority in the analysis of the system. We will keep you informed.

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