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A Holistic Approach for Technical Product Optimization

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***Abstract*—**Holistic methods covering the development process as a whole – e.g. systems engineering – have established themselves in product design. However, technical product optimization, representing improvements in efficiency and/or minimization of loss, usually applies to single components of a system. A holistic approach is being defined based on a hierarchical point of view of systems engineering. This is subsequently presented using the example of an electromechanical flywheel energy storage system for automotive applications.

***Keywords*—**Design, product development, product optimization, systems engineering, flywheel energy storage.

I. Introduction

OPTIMIZATION of products focusing on technical – usually quantifiable – criteria aims at effects on the highest levels of systems and – in many applications – approaches its maximum asymptotically. This does not necessarily result in optimization of customer benefit. Defining technical optimization as optimal balance between the product itself and its application, however, opens another approach to make use of previously untapped potential. Based on the system hierarchical point of view of systems engineering it can be differentiated between two divergent methodical approaches for optimization. Let a technical system or product be a set of subsystems and itself part of a super-system, the optimization can occur both *directly* and *indirectly* as shown in Fig. 1. A synthesis of both these concepts supports the creation of a holistic approach to master technical product optimization. The methodical combination of *direct* and *indirect* optimization finally results in holistically-oriented product improvement, taking into account all requirements ranging from component- and highest system level, including *vertical* (between system levels) and *horizontal* (on system level) dependencies, as well as those of the environment. This approach is being presented using the example of an electromechanical flywheel energy storage system (or FESS). On the one hand, technical measures at component-level are shown, leading to a gain in efficiency of the system itself (independent of the super-system). On the other hand, the specific characteristics of an electromechanical flywheel are compared to those of alternate principals of storage, deriving advantageous characteristics of the super-system as well as its application and overall conditions, while at the same time taking into account trends between component- and environment-level.

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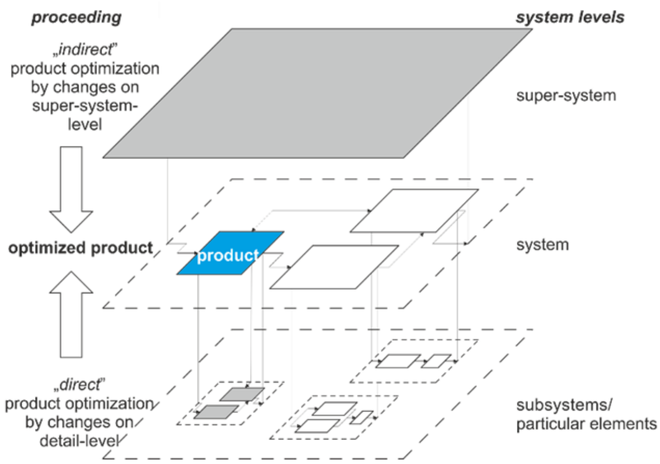

Fig. 1 Product optimization related to system hierarchy, based on [1]

II. System Description of Flywheel Energy Storages

Energy storage can be seen as one of the most important technological challenges of our century. Not only the increasing number of mobile devices such as cell phones or laptops, but also the transition to hybrid or electric vehicles stresses the importance of developing efficient energy storage systems. The trend of electrification of the drive train is driven by the urge to reduce CO_2 emissions and gain an economic and political independence from imported fossil fuels. However, zero emission vehicles (ZEV) are only as effective as their prime energy source. This means, that renewable energy sources such as wind and solar must be used to charge the vehicles. Again, these volatile sources require energy storage at a large scale.

Despite constant advances in chemical energy storage, conventional batteries do not always lead to complete customer satisfaction due to shortcomings such as limited charge cycles, temperature dependence and difficult recycling. Flywheel energy storage systems are based on the simple physical principle of storing energy in a rotating mass. The content of energy (or state of charge) can easily be determined by using the simple equation:

$$E_k = \frac{1}{2} * I * \omega^2 \quad (1)$$

While it is obvious that the most elegant way to reach high energy densities is to increase rotational speed (doubling the *rpm* results in four times energy content), the strength of the rotor material represents a theoretical limit because of centripetal forces.

The equation below describes the maximum tensile stress σ of a rotating disc, whereby r_a is the outer radius of the disc:

$$\sigma_{max} = \rho * \omega^2 * r_a^2 * \frac{3+\mu}{8} \quad (2)$$

Though flywheels have been used for centuries as pottery wheels or in steam engines, they first became popular in the 1970s as vehicular energy storage when oil prices skyrocketed [2]. A typical configuration of a vehicular FESS is shown in the image below (Fig. 2).

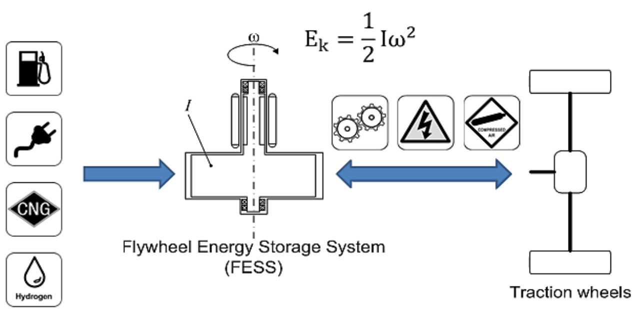

Fig. 2 Bloc diagram of vehicular FESS

Power can flow to the traction wheels by various means of energy transport (mechanic, electric, etc.) and since the process is reversible energy can be stored in the flywheel during braking. Furthermore, the flywheel can be combined with a number of prime movers in various hybrid vehicle topologies. The flywheel's burst containment is normally evacuated to reduce windage losses.

Some key-features of mobile flywheel energy storage units used in vehicles can be listed.

Advantages of flywheel energy storage systems:

- Capable of handling high power flows → Ideal for regenerative braking
- Energy content only depends on flywheel speed and moment of inertia → Potential for high energy densities
- Total deep discharge does not harm the storage device
- High number of cycles possible without decreasing performance
- No dependency on operating temperature
- Long service intervals and lifetime (depending on bearing type)
- Mechanical and electrical energy transfer possible
- Content of energy can be exactly quantified by measuring the rotational flywheel speed

Despite all these theoretical advantages, which are especially beneficial to the automotive industry, flywheels are currently primarily used as uninterruptable power supplies (UPS). Unlike in chemical batteries, power and energy content of an *electro-mechanical* FESS can be designed independently. In the case of an electromechanical flywheel, a motor-generator is connected via a shaft to the spinning mass. While the rotor material and design determine the maximum speed and hence the energy content, the specifications of the electromotor determine the maximum available power.

As indicated in Fig. 2 energy can also be transferred mechanically. In this case, high differences in rotational speeds between traction wheels and the flywheel itself need to be bridged. This is usually done via a series of gears, clutches and a continuously variable transmission (CVT).

In this publication, all *direct* and *indirect* product optimization applies to an *electromechanical* FESS. Advances in power electronics and electric motors as well as the possibility to place the device anywhere in the vehicle without depending on a direct mechanical connection with the drive train stress the potential of this solution. However, as will be shown in Section III, complex interdependencies between system components pose technical challenges, which hinder the development of an FESS with characteristics close to those of an idealized *reference energy storage device*. Still, the specific properties of an FESS can be fully exploited if holistic product optimization is pursued and the entire system – as shown in Fig. 3 - is considered (compare section V).

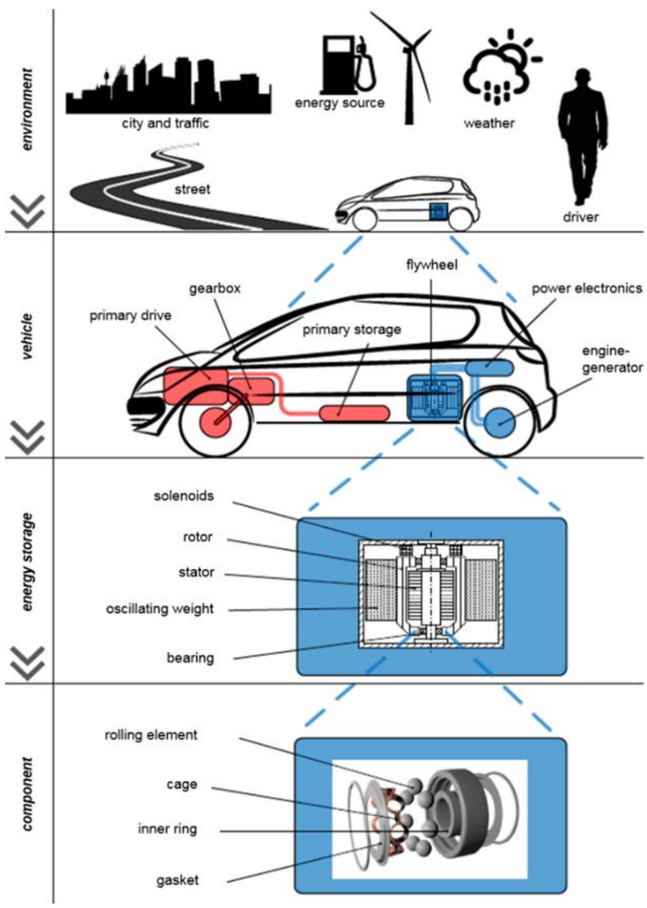

Fig. 3 System hierarchy of an electromechanical flywheel for automotive applications

III. Direct Product Optimization

Direct product optimization is defined by technical and/or constructive modifications and hence results in a change of the system (in present case the FESS). This represents the classic, conventional approach of product optimization and is the one usually pursued by engineers. Quantifiable optimization results are based on given quantifiable technical criteria. Measures of optimization – defined as modifications on an existing product – are performed on the lowest hierarchical (or detail) levels and finally result in an optimized whole in terms of *vertical synthesis*. Many well-established methods for component design support this approach [3]. Modifications at detail level offer further potential for optimization if additional *horizontal dependencies* exist. In contrast, the inability to accurately define the effects of potential modifications might lead to complex multi-dimensional problems (Fig. 4).

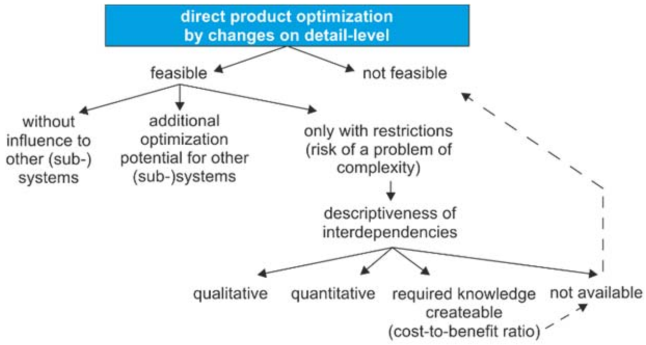

Fig. 4 Scenarios of direct product optimization

Direct product optimization – if feasible – can be divided in three categories (Fig. 4 and Table I), depending on its influence on other (sub-) systems. The logical first step in any conventional technical development process is the optimization of single, individual components or sub-systems without any interdependencies.

Focus is set on whichever component needs to be optimized and system behavior/interdependencies, as listed in the examples below, are initially neglected:

- Improved material selection may enable cost reduction
- Alternate manufacturing process may enable cost reduction
- Notch design may improve strength and fatigue behavior
- Design of tribological parameters may increase efficiency

However, if the existing product conforms to the state of the art, little or no improvement is possible. If components or (sub-) systems show a potential reserve in the sense of surpassing certain criteria, a new degree of freedom in optimization of the whole system arises. For example, a reduction of size of a component that is over-dimensioned may create more space for improving a neighboring part. However, quite often isolated improvement of a single component results in deterioration of others. Using the example of a simple shaft with bearings, this circumstance can be explained:

The target properties “service life” and “shaft strength” are determined by the bearing system and the shaft material, as well as geometric values such as bearing clearance, diameter, notch radii, etc. While optimization of these parameters offers potential reduction of space or cost, aspects such as overall stiffness, resonance frequency, thermal properties or similar, may be neglected and lead to inferior overall performance. As will also be shown in Fig. 5 the complexity of the matter is based in the *multi dimensionality* of the optimization process. Even more difficulties arise if no quantifiable parameters are available to characterize system interdependencies. A quantification or fundamental investigation of these relations may lead to significant test and research effort that can only be justified if vital findings with respect to holistic optimization can be expected.

TABLE I
Overview of Measures and Challenges in Direct Product Optimization

Influence on other (sub-) systems	Examples of target properties	Measures for optimization	Potential	Challenges	Comments
Does not apply	loading, price reduction, efficiency, increased service life	Design according to state of the art – according to design guidelines	Exploiting potential without any disadvantageous effects	Usually little potential for optimization	Fully exploited potential for optimization characterizes a fully developed design. Hence, there is usually not much usable reserve
Additional potential for optimization	price size weight stiffness efficiency service life	Creating potential for optimization for other (sub-) systems by transformation of requirements	Creating advantages for other (sub-) systems	Self-financing or cheaper results	Existence of safety margin allows free and unhindered design in the sense of well-balanced optimization
Only feasible under restrictions	price size weight stiffness efficiency service life	Well-adjusted modification of entire assembly and/or design of (sub-) systems	Finding a holistic optimum by minimizing disadvantages through consideration of interdependencies	Problem due to high complexity may occur, especially in the case of non-quantifiable criteria/interdependencies	Exploitation of safety margins requires excellent knowledge of loads and possible damage

Concerning the optimizing of vehicular FESS, nowadays, requirements for mobile energy storage devices are usually defined by energetic simulation of the entire vehicle during a standardized driving cycle.

The result of such simulation is specification of a theoretical *reference energy storage system*, such as *energy density, power,* and *self-discharge rate*. *Direct optimization* of an FESS aims at reaching these specification by modifying internal components in the (sub-)system of the storage device (Table II).

TABLE II
OPTIMIZATION GOALS AND COMPONENT MODIFICATION OF FESS

Goal	Modified component
Reduction of self-discharge	Bearing design and Vacuum system
Increased energy density	Rotor design
Increased power	Electric motor
Increased service live	Bearing design
Increased safety	Rotor design and Safety housing

While at first glance, it seems logical to pursue independent optimization of each component listed in Table II, complex interdependencies between elements in an FESS make isolated optimization nearly impossible (compare [4]).

The following example (Fig. 5) starts with the simplest “low-cost” solution: A cylindrical disc operating at ambient pressure, connected to the drive train via a CVT.

This concept implicates high windage losses. These losses can be reduced by including the flywheel in a vacuum housing. However, this does not only increase system complexity but also results in shaft feed-through and vacuum pump losses. If the concept is modified by switching to electrical energy transfer in order to hermetically seal the vacuum chamber, thermal problems will arise soon because there is no convection to cool the motor. In addition, the lubrication of the bearings is far more complicated. Introducing a power limit for the electric machine and using a gimbal mount in order to be able to use magnetic bearings results in a significant increase of costs and space while it lowers crash-safety.

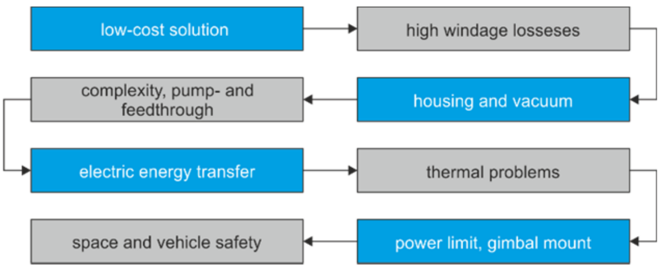

Fig. 5 Flywheel as multidimensional optimization process [2]

The design of the perfect flywheel energy storage system is therefore a *multidimensional optimization problem*. It is obvious, that – if cost reduction is kept in mind – not all the goals listed in Table II will be reached by isolated modification of sub-components. The properties of the FESS reached in real life will be inferior to the ones determined by the energetic simulation. Still, *indirect product optimization* as described in the next section offers the option to efficiently operate mobile flywheel storage devices with given sub-optimal properties.

IV. INDIRECT PRODUCT OPTIMIZATION

Product optimization can also happen *indirectly* by specific selection and/or design of the *super-system* itself or its environment. Following this approach, the overall conditions for a most effective and efficient application of an existing system are made available. Hence, the primary approach is not to intervene on an already devised system but at the level *above* the system. The goal of *indirect product optimization* is to make use of the *super-system* (via advantageous use and selection of overall conditions) to facilitate the creation of an environment that allows for optimal application of a product without changing the product itself (Fig. 6).

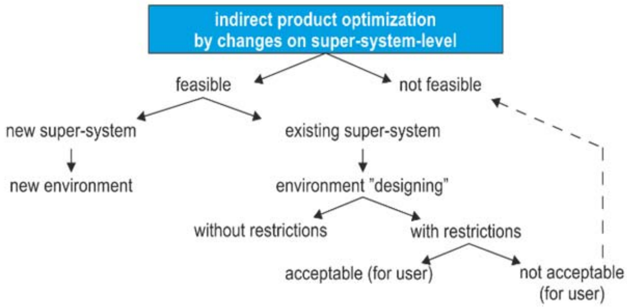

Fig. 6 Scenarios of indirect product optimization

In the case of FESS, *indirect product optimization* means that applications and operating conditions need to be found, which favor flywheel-specific properties such as low energy density or high self-discharge. The more concept-immanent properties can be taken into consideration, the more likely a concept will be successfully transferred into a final product. This requires an extensive system analysis, taking into account all influencing factors and parameters as shown in Fig. 7 (compare [5]).

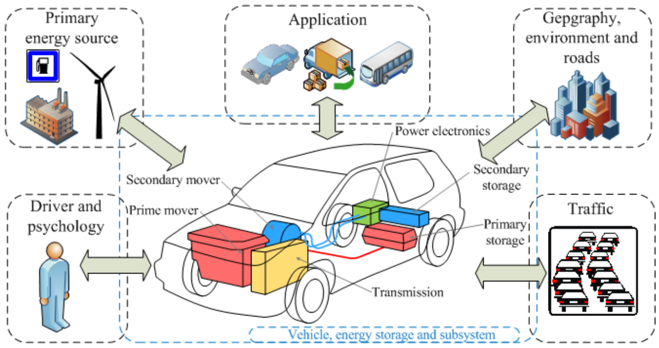

Fig. 7 Super-system and environment of automotive FESS

As mentioned in section III, properties of modern FESS are usually far from those determined for the *reference energy storage device*. Self-discharge due to frictional losses and inferior energy density can be listed as major shortcomings. However, this does not necessarily mean, that other advantages (as listed in section II) cannot be exploited. A suitable application, mitigating or ignoring sub-optimal FESS properties needs to be found or created. Public transportation in urban areas is a well suited application for flywheel energy storage due to the following reasons.

- Professional drivers can "learn" an effective way of driving. The following diagram (Fig. 8) shows the recuperable energy over the vehicle deceleration, indicating that coasting without breaking results in dissipating all the kinetic energy. Regenerative breaking requires decelerating the vehicle in a certain range.

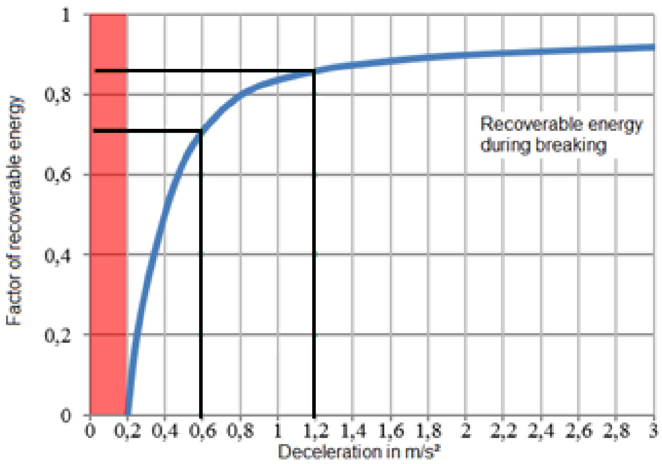

Fig. 8 Recuperable breaking energy share over deceleration values computed for a transit bus [6]

- Efficiency is the primary objective when it comes to selecting the vehicle, so buyers are willing to invest in FESS technology.
- Continuous operation of the fleet results in shorter payback periods.
- And finally – and this might be the most important factor of all – the duty cycle of urban public transportation is usually highly dynamic offering a high amount of recuperable energy. It is hence *suitable*.

However, there is a second property that is relevant: The *predictabilit*y of the duty cycle. The idea behind this concept is visualized in Fig. 9.

The horizontal axis represents the *predictability*, whereas the vertical axis shows the approximate *suitability*. A rail vehicle, like a tramway, offers a high predictability of loads and is very suitable for flywheel application. An intercity train on the other hand offers equal predictability of the loads, but hardly any recuperable energy due to the stationary duty cycle.

The *predictability* of the duty cycle is hence as *necessary* but not a *sufficient* requirement for the application of flywheel energy storage.

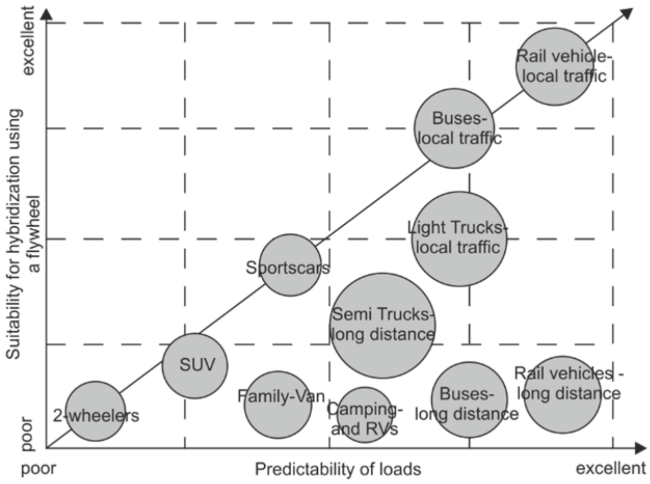

Fig. 9 Predictability of loads and suitability for vehicular FESS application

V. A Holistic Approach

Direct product optimization is a well-established procedure in product development. Requirements – i.e. quantifiable criteria – represent the target figures, their achievement the development goal. The exploitation of technical potential of specific components, modules or the whole system is thereby not categorically aspired, respectively necessary. Moreover, a low-cost solution, which is "just good enough" and barely meets the requirements, is aimed. Technical limitations of specific components may then represent a bottleneck and determine the performance of the entire system. In this case the potential of "sub-challenged" components or modules remains unexploited. This is exactly the point where *indirect product optimization* comes into play. It offers the possibility to use specific conceptual strengths of an existing product, while at the same time mitigating the significance of the product's shortcomings. *Indirect product optimization* tries to find an ideal application for theoretical or already realized solution (i.e. the initial product). This product has been the result of a *preceding iterative direct optimization process*. During such an iterative, direct optimization process it is possible to verify if certain criteria have been met and even specific characteristics of the entire system can be recognized. In the case of an actual product, practical experience gained during operation facilitates this process.

Indirect product optimization extends the conventional optimization process by introducing a specific existing system/product with all its characteristics to new "optimized" operating conditions. Virtually, the *super-system* and its environment are being aligned with the system/product, matched and harmonized. This approach represents a methodical upward extension of the conventional *V-model* (Fig. 10). This means *direct product optimization* is extended and combined with *indirect product optimization*.

Quantifiable requirements coming from *super-system* and environment represent the link to the *V-model*. The selection of a new application or modification of the *super-system* should therefore aim at providing idealized conditions for the specific product characteristics.

Apart from the principle range of application (automotive vs. civil engineering, etc.), environmental conditions define the requirements of the *super-system*. The more precisely these requirement can be defined and quantified the easier it is to match system requirements and product characteristics. This process is also executed iteratively just like the process of *direct product optimization*. The complexity and difficulty of holistic, combined product optimization depends on the number of variables and the type of occurring interdependencies.

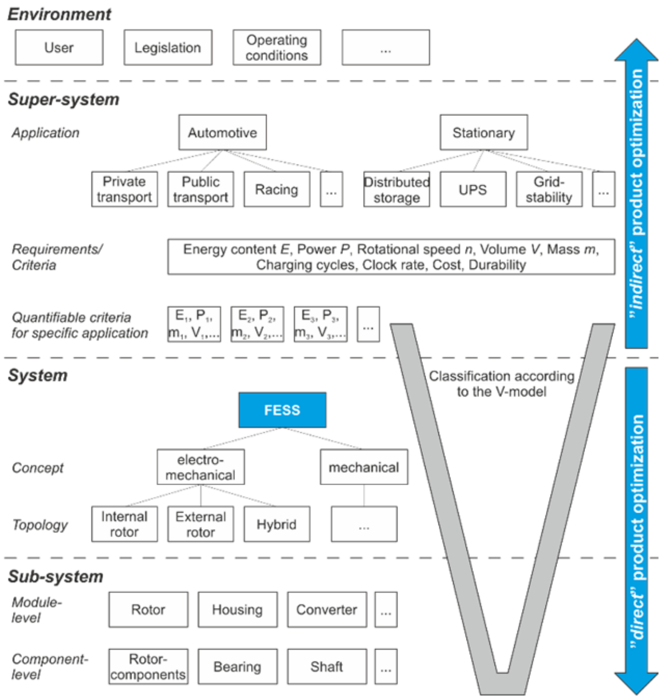

Fig. 10 Combination of direct and indirect product optimization and their position in the V-model [7] based on the system FESS

Fig 10 can be described as follows. Depending on initial, quantifiable product requirements, a first concept or topology is chosen. Further detailing is done by modification or redesign at *sub-system level*. (i.e. components are modified.) According to [7] the ascending (right) branch of the "V" represents system integration with continuous verification. This allows the acquisition of experience and know-how related to properties and behavior of the system and its components. Consequently, specific product properties and potential for future improvement can be derived. This represents the basis for evaluation of the suitability of a new or modified *super-system* and its environmental conditions for an existing product. In this case, mobile and stationary FESS application is compared based on user behavior and expectations, driving cycle and ambient conditions to name but a few. If a product's requirement and property profile shows high congruency, adaption and optimization of the system can be achieved by exploiting initially untapped potential in the sense of direct product optimization.

VI. Conclusion

The benefits and shortcomings of *direct* and *indirect product development* were discussed in detail using the example of *flywheel energy storage systems*. Due to their special operating conditions such as vacuum and high rotational speeds FESS currently do not reach satisfactory energetic properties if only *direct optimization* is pursued. Even more so, complex interdependencies between components at sub-system level lead to a *multi-dimensional optimization problem* and sub-optimal system behavior.

A *synthesis of direct and indirect technical product optimization* represents a holistic approach which may enable efficient system design and full exploitation of technical properties, not only in the case of FESS but technical products in general.

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