Design for Circularity with ePOP

A Software Solution built for Powertrain Optimisation of Performance, Cost and Sustainability

Wiktor Dotter, ZeBeyond Ltd
Dr David Hind, Drive System Design Ltd

1 Abstract

The concept of "Design for Circularity" in sustainable transportation emphasizes the crucial integration of circularity considerations right from the initial stages of Research and Development (R&D). This approach underscores the significance of making early decisions concerning sustainable materials, optimized powertrains, and reduced energy consumption.

One core focus of this approach lies in balancing various components like gearboxes, electric motors, batteries, and inverters to suit specific applications. By emphasizing the synergy between these elements, engineers can make well-informed decisions, enhancing efficiency and promoting sustainability.

Moreover, the emphasis is on collaborative efforts that transcend individual subsystems, extending into the entire supply chain. Enabled by digital software solutions, this collaboration allows seamless cooperation between Original Equipment Manufacturers (OEMs) and material suppliers. OEMs gain valuable insights into the advantages of recycled materials across subsystems and system levels. Simultaneously, it empowers Tier5 suppliers and above to showcase their sustainable solutions at a broader, systemic level. This collaborative approach signifies a new era of sustainable transportation, where stakeholders work cohesively towards a shared goal.

The collaborative ethos is exemplified through a compelling use case involving power electronics, specifically comparing IGBT and SiC inverters. While these components might entail higher initial costs at the subsystem level, the research illuminates their potential to significantly reduce overall expenditure. This reduction is achieved through downsizing batteries, indicating a nuanced approach to cost analysis that extends beyond immediate expenses.

In essence, "Design for Circularity" serves as a guiding principle for the engineering community. By embracing circularity principles from the early stages of R&D, considering subsystem-to-system tradeoffs, and fostering collaborative ties within the supply chain, this approach paves the way for a more sustainable and efficient transportation landscape.

2 Introduction

In the ever-changing landscape of the automotive industry, a profound transformation is underway – a shift towards sustainable transport and manufacturing. While it might seem relatively easy to create a car with zero tailpipe emissions, the real challenge lies in constructing a vehicle that maintains zero emissions throughout its entire lifecycle – from its initial creation to its eventual retirement. This comprehensive approach, often referred to as cradle-to-grave sustainability, demands a meticulous re-evaluation of every component and process involved in automotive production and usage.

This disruption not only signifies a change in how vehicles are powered but also opens doors to innovative products and reshapes supply chain dynamics. However, amid this wave of change, a dual narrative unfolds. On one side, there are exciting prospects for manufacturers, leading to the formation of new products and novel supply chain configurations. Simultaneously, there looms a threat, casting a shadow on many established players in the industry. Original Equipment Manufacturers (OEMs) and Tier 1-4 suppliers find themselves at a crossroads. The vertical integration pursued by OEMs squeezes out many sub-suppliers, reshaping the business landscape drastically.

Amidst this intricate web of opportunities and challenges, the need to "navigate the disruption" becomes not just a call to action but an urgent imperative. The industry requires swift responses, grounded in facts and facilitated by collaborative tools. These tools are essential not only for optimizing interactions from subsystem to system but also for fostering fruitful collaborations between material providers and OEMs. Fast facts and efficient collaborative frameworks are the compass guiding manufacturers through this transformative journey.

In this context, this paper aims to delve into the heart of this disruption, exploring strategies and solutions that enable not just adaptation but thriving in this new automotive era. By bringing together real-time data, collaborative methodologies, and a forward-thinking approach, this paper serves as a vital resource, empowering stakeholders to make informed decisions, foster collaborations, and steer the industry towards a more sustainable and prosperous future.

3 Design for Circularity

Fig. 1 Enabled Strategy Focused decision making has to entail iterative and multi-dimensional simulation.

3.1. Design for Circularity: Navigating the Complex Terrain of Sustainable Automotive Engineering

In the ever-evolving landscape of automotive engineering, the early concepting stages of Research and Development (R&D) stand out as the epicenter of transformative potential. This phase, often regarded as the crucible of innovation, holds the key to making decisions that reverberate throughout a vehicle's lifecycle, making it a pivotal juncture in the pursuit of circularity.

3.2. The Early R&D Design Stage: A Crucible of Impact

The significance of the early R&D design stage cannot be overstated. It is here that decisions are made, choices are crystallized, and the blueprint for a vehicle's sustainability journey is laid. The impact of these early choices resonates across manufacturing, usage, and eventual recycling or disposal. This phase becomes a canvas on which the intricate tapestry of circularity is woven. Engineers, sustainability experts, and finance professionals should converge here, each with their unique perspectives, forming a diverse yet interdependent collective. However, therein lies the challenge - to harness this diversity for holistic decision-making.

3.3. Understanding the Consequences: The Ripple Effect

Every decision made in the early stage of R&D sends ripples across the entire ecosystem. Understanding these consequences is paramount. A seemingly minor choice concerning a component material or a particular powertrain configuration can have far-reaching implications. These ramifications extend beyond the engineering realm into sustainability, finance, and even consumer perception. Recognizing and mitigating these effects require a multifaceted approach. See Fig.2.

3.4. The Challenge of Collaboration: Organizational, Process, and Human Dynamics

Collaboration, the linchpin of holistic decision-making, presents a multifaceted challenge. Organizational structures often segment teams, creating silos between sub-system engineers, sustainability experts, and finance professionals. This lack of communication inhibits the flow of vital information. Moreover, diverse educational backgrounds further complicate the scenario. Engineers, environmental scientists, and financial analysts often speak different technical languages, figuratively and literally. Bridging these gaps necessitates not just communication but a shared understanding and a common language, ensuring that the decisions made are comprehensive and impactful.

3.5. Application and Use Cases: Tailoring Sustainability

Moving from theory to application, the challenge intensifies. Different vehicle segments - from passenger cars undergoing rigorous WLTP drive cycles to commercial vehicles navigating urban jungles and off-road beasts conquering challenging terrains - demand tailored solutions. Circular design principles must align seamlessly with the unique demands of each application, ensuring optimal performance, minimal environmental impact, and cost efficiency.

3.6. The Connected Supply Chain: Beyond Current Knowledge Base

In the quest for circularity, looking beyond the current knowledge base is indispensable. Embracing the entirety of possibilities is a game-changer. Enter ePOP software - the linchpin connecting disparate threads within the supply chain. This digital solution transcends conventional boundaries, enabling real-time collaboration. It empowers engineers, sustainability experts, and financiers to explore, assess, and decide collectively. ePOP software not only widens the spectrum of options but accelerates the decision-making process. It transforms a labyrinthine array of choices into a streamlined, efficient pathway towards circularity.

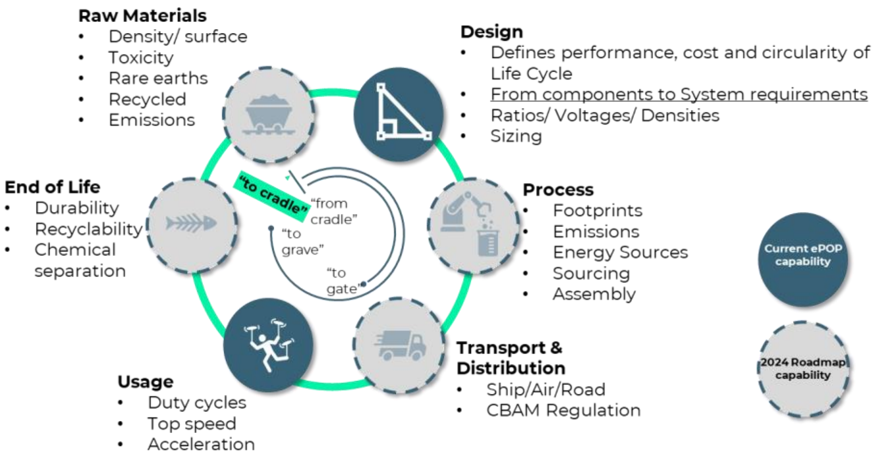

Fig. 2 Supply Chain to adopt its structures to the product lifecycle to enable product selection based on each stage in the product lifecycle.

3.6. Summary

In essence, the early R&D design stage is the crucible wherein circularity either finds its foundation or falters. It demands not just innovation but collaboration, comprehension, and the courage to explore beyond the known. As the automotive industry hurtles towards a sustainable future, understanding the significance of this phase and embracing collaborative digital solutions like ePOP software becomes not just a choice but a necessity. Together, by navigating the complexities and challenges, we can forge a future where circularity is not just a concept but a tangible reality in every vehicle on the road.

4 Collaboration

Collaboration across all parts of the vehicle lifecycle must be at the heart of the movement towards truly sustainable transportation, right across the lifecycle, from raw material extraction through to end of life, as illustrated in Fig.3. In the design stage collaboration is required across the supply chain to ensure that the optimal technologies are available for designers to integrate into products, and are mature enough to enter mass manufacture. In turn, design engineering teams must ensure that the near and far future requirements of the systems being designed are clear to manufacturers and the supplier chain to ensure that the right investments are made in the supply chain to pave the way for future powertrain developments rather than simply just relying on what is available today.

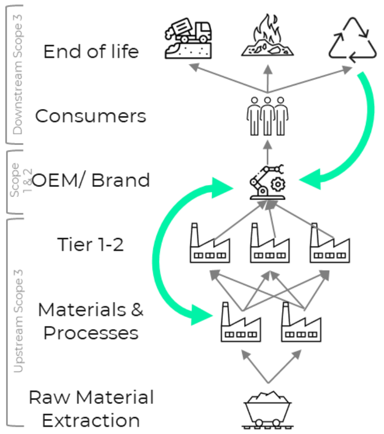

Fig. 2 Supply Chain required to be dynamic beyond it's current structures

4.1 Organizational collaboration

Collaboration between specialized teams within their respective silos presents challenges. It becomes even more daunting when diverse professionals need to collaborate in a fact-based, bias-free manner to identify the optimal system candidate aligning with the overall strategy. Complicating matters, conflicting targets often emerge; engineering goals like weight, range, speed, and energy

consumption may conflict with environmental concerns or higher production costs. The central question remains: how can organizations reconcile their net zero objectives with product performance and profitability targets for the next-gen platform in an evidence-based manner?
Certain organizations have initiated cross-silo collaboration processes involving engineering, sustainability, finance teams, and even integrating product lifecycle performance data (PLM) in their approach. Typically, these teams align their goals by comparing 2-3 concept ideas, often using something as straightforward as an Excel spreadsheet. However, the real challenge lies not in the tool itself but in instigating internal change management processes. Encouraging these three crucial sectors to collaborate during the earliest R&D stages, and incorporating PLM data, is essential. This approach ensures a comprehensive perspective, leading to the best possible outcome and potentially enhancing product life, reducing costs, and minimizing environmental footprints over the lifecycle of the product.
Given that the ultimate decision rests with the board level, which may consist of investors unfamiliar with these disciplines, ePOP plays a pivotal role. Its design allows for easy comprehension even by generalists, expediting decision-making processes and facilitating a smoother navigation through disruptive challenges.
Although the silos are visibly distinct at both the organizational and discipline levels, their impact permeates deep within engineering, reaching even the sub-component teams. Consider the inverter and power electronics sector as an illustration: a noticeable divide exists between hardware and software competencies. These factions often find it challenging to collaborate effectively toward shared objectives, with gate driver design, thermal and mechanical interface management, general electronics design, and power modules selection and management each having their own sub-component requirements. This internal fragmentation underscores the complexity faced within engineering, hindering seamless collaboration and cooperation across diverse expertise areas.

4.2 Sub system to System Collaboration

Within an EDU a number of key subsystems exist, these systems each have their own opportunities and main operating island (Fig. 4) within their design space to optimise the subsystem design. This can lead to other subsystems being compromised because decisions taken in isolation can enforce limitations on other subsystems. An overall view of the system design space is needed to ensure that subsystems are optimised collectively to ensure the optimal system is engineered for the requirements and use case. Subsystem options and trade-offs are extensive, the following sections explain for some of the key subsystems the options that designers must select between before diving deeper into the power electronics subsystem.

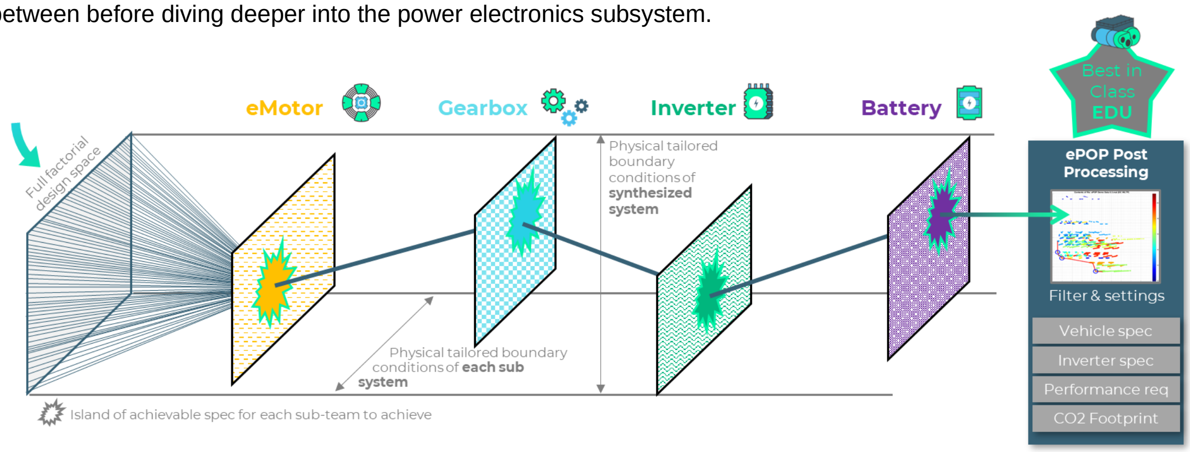

Fig. 4 Each Sub System has individual optimum operating islands that need to align on system level in order to reach the consolidated optimum.

4.2.1 eMotor: PM vs. Induction Motors

Most electric vehicle powertrains utilise motors that include permanent magnets (exceptions include Tesla Model S [induction] and Renault Zoe [synchronous wound field]).
However, the materials required for these magnets are not only expensive, but have also seen volatility in costs. As more electric vehicles are produced, it could be expected that demand will continue to rise, which could impact prices, depending on supply.
By including these materials in their powertrains, powertrain/vehicle suppliers and manufacturers are exposed to these costs and volatilities.
Many manufacturers are seeking alternative designs that minimise magnet content, or alternative technologies eliminate them altogether. Several trade-offs must be considered, including:

- Positives = no magnet, so motors themselves are typically cheaper, and immune to magnet cost volatility, Magnetic fields can be ‘turned off’ to eliminate back emf voltage, particularly useful when acting as a second EDU in AWD applications (no need for mechanical disconnect as with PM motors)

- Negatives = less power/torque dense -> typically ~20% reduction in power for same size, lower (peak) efficiency,
- Other = different efficiency map shape (means different operating conditions are preferred -> just swapping into existing designs not optimal)

The ePOP tool allows these relative strengths and weaknesses of different motor types to be evaluated fairly and objectively. Each motor can be paired with transmissions that enable it to operate in its most favourable conditions, allowing like for like comparisons against metrics of vehicle performance or energy consumption. These studies allow us to understand under what applications and circumstances magnet free motors can offer legitimate alternatives, or complimentary options, to permanent magnet motor-based powertrains.

4.2.2 Gearbox: 1-speed vs. 2-speed (or more) transmissions

Utilising a single speed transmission is a common approach in electric vehicle powertrains. The transmissions themselves are cheap and simple, enabled by the wide operating speeds many traction motors are able to operate. However, this assessment may be simplifying what is actually a more complex question.

Whilst a typical traction motor may have a wide range of operating speeds, its performance varies significantly over these conditions.

The ratio selected for a single speed transmission must enable all vehicle targets to be met, such as top speed, acceleration, or gradeability, as well as maximising efficiency in order to minimise energy consumption and achieve a vehicle range that alleviates ‘range anxiety’ that still surrounds electric vehicles in the public eye. Often, a compromise must be reached.

A two (or more) speed transmission allows these targets to be shared among the different selectable gears in the transmission; for example, achieving acceleration targets in 1st gear, and top speed targets in 2nd. A smaller, cheaper traction motor may be able to achieve these with carefully selected gear ratios.

Not only that, but multiple selectable gears within the transmission allows for greater control of the motor operating conditions, relative to the vehicle; the motor can operate in more a more efficient region by selecting the most suitable ratio available in the transmission.

However, implementing a multi speed transmission requires additional costs, not only from the additional parts within the system itself, but from engineering design and development costs associated with the more complex system.

ePOP allows us to understand in what applications these additional costs can be offset by the benefits, not only at the system level, but at the vehicle level itself, where battery size and mass is a further contributing factor.

4.2.3 Inverter

Silicon based IGBTs are the traditional automotive standard for inverter power modules. However, the use of silicon carbide (SiC) based alternatives is now becoming widespread, with some already utilising SiC technology in vehicle mass production programmes. In new development programmes the use of SiC is frequently mandated by system developers looking to position themselves on the front edge of market trends.

As is often the case with emerging technologies, costs are high relative to more established products. However, over time, it is expected that costs will further reduce, making the benefits of the SiC technology more accessible for a wider range of applications. Power electronics is still an area of rapid growth and development and so this pattern of emerging technologies having a high price tag which impacts their viability is set to repeat several times over in the coming years with emerging technologies coming to market.

The challenge for all suppliers and vehicle manufacturers is **when** to commit to the new technology; too early and one is left paying elevated costs, too late and one may be several steps behind their competitors and catching up while remaining credible becomes a challenge. ePOP is capable of performing studies to support and inform these kinds of decisions:

- SiC based inverters exhibit reduced switching losses compared to IGBTs and are thermally more efficient, reducing cooling system requirements and increasing power density.
- SiC based inverters allow higher switching frequencies. With a systems approach this enables higher motor speeds to be achieved, which in turn allows smaller motors to be design throughhigher pole motors with reduced stator yoke thicknesses, increasing system power density.
- The above two points are performance based, but ePOP also allows examination of the value proposition, and the impacts of cost trajectories of different technologies. By investigating the impact of the expected costs forecast of SiC based inverters, ePOP can provide insight not only on what specification of powertrain could optimally utilise this technology, but also when it is best to develop it.

4.3 Connected Supply Chain Collaboration

Power Electronics is an area of powertrain system design which offers a large potential for gains when a holistic system view is applied. 2 level inverters dominate the Power Electronics sub-system architecture, and many will be familiar with the IGBT vs SiC technology debate discussed in 4.1.3. But a closer look at this complex subsystem reveals the potential for a greater number of systems influencing design opportunities that come with new competing technologies. These design decisions not only require designers to consider the cost/performance impact on the end user, but also the availability and maturity of the supply chain to support mass manufacture.

With facilities capable of supporting mass production programs costing millions, it's key that the supply chain works with design engineers to ensure the right technology is invested in to enable future powertrain designs to be viable, while also securing the futures of the suppliers themselves. Many areas of inverter sub-system optimization exist but are often overlooked, they include switch technology (IGBT Vs SiC Vs GaN), Battery voltage (400V, 800V, 1200V), switch construction (Solder Vs Sinter Vs Hybrid), Interconnect technology, Converter architecture (multilevel (NPC, ANPC, Flying capacitor, modular) vs 2 level), number of phases, bus bar design, DC link capacitor design. Clearly with all of these choices design tools are required to understand which options offer the largest potential for overall system improvement and therefore justify additional component cost and/or supply chain investment to support.

5 Power Electronics Study and Results Use Case

This paper presents a comparison between a system that utilizes an IGBT inverter, and one which uses a SiC Inverter. The aim is to firstly highlight the benefits that can be achieved with a systems-based approach, but also how this thinking can lead designers towards optimal systems designed collaboratively with the supply chain in mind. Power electronics in particular is still a field in which there is a large amount of new competing technology emerging.

The case study presented is for a typical C-segment EDU. Using the ePOP tool from ZeBeyond, thousands of powertrain architectures have been compared and evaluated against a number of key parameters to highlight the system level impacts of different technology selections at the sub-system level, in this case SiC and IGBT power modules. The ePOP tool by ZeBeyond was originally developed by DSD based on their extensive powertrain design experience. ZeBeyond still work very closely with Drive System Design Ltd (DSD) to capture the latest technologies and market trends across the EDU system.

Initially system level requirements are defined, and a number of design options are entered into the ePOP tool. An analysis is then performed to evaluate vehicle performance based on the requirements allowing comparisons to be made against thousands of powertrain configurations. These configurations include both IGBT and SiC based systems and their impact can be observed at the system level. Fig.5. shows the impact of Powertrain cost and (normalized) energy consumption in kWh, it's clear that the SiC based systems are more costly to build, but they also have a lower energy consumption per 100km travelled, meaning either the system could have a smaller battery, or could be offered with a higher range therefore gaining market advantage.

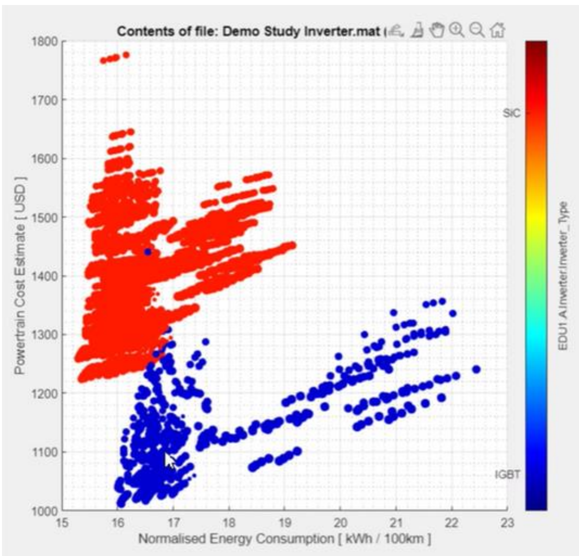

Fig. 5 Powertrain Energy Consumption Vs Cost highlighting the difference between IGBT (blue) and SiC (red) based solutions

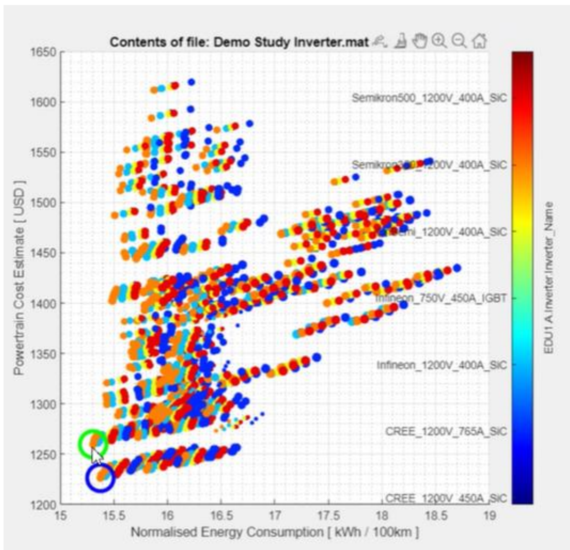

Fig. 6 Comparison of SiC based solutions utilising different physical power modules

A deeper look into the power electronics impact is gained by looking at the impact of specific power module selection, as shown in Fig. 6. The impact of motor and transmission design is captured here but the influence of the power module is clearly seen, with systems featuring the Infineon and Semikron 1200V, 400A power modules offering the lowest cost and lowest energy consumption. Fig. 7 focuses on the lowest powertrain cost, lowest energy

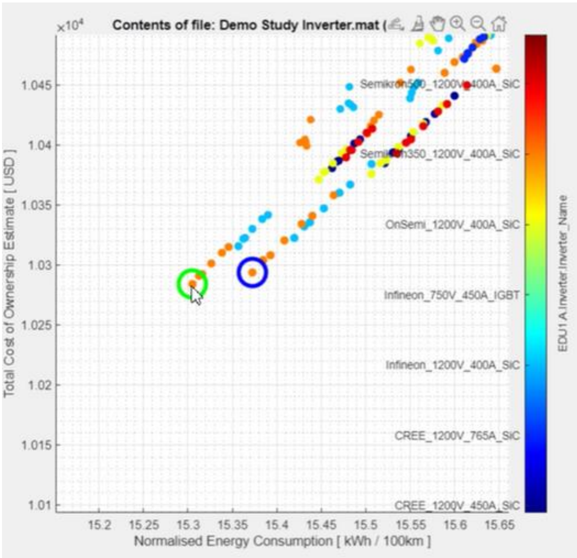

Fig. 7 It is shown that the lowest cost, lowest energy consumption systems are provided by a specific power module

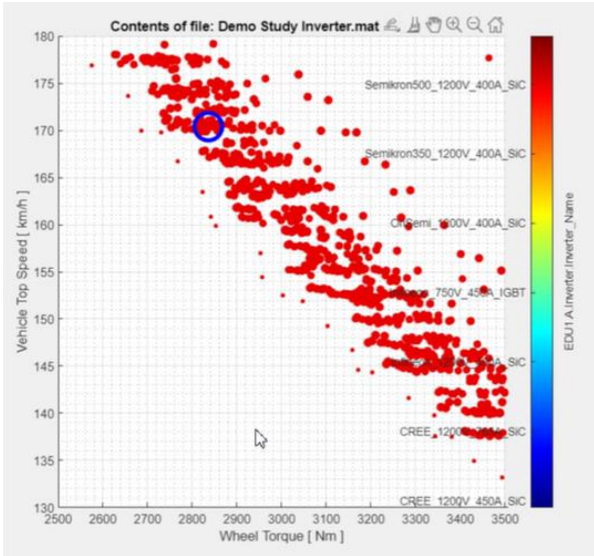

Fig. 8 Results using the selected power module can now be seen and optimised for motor, gearbox and battery selection

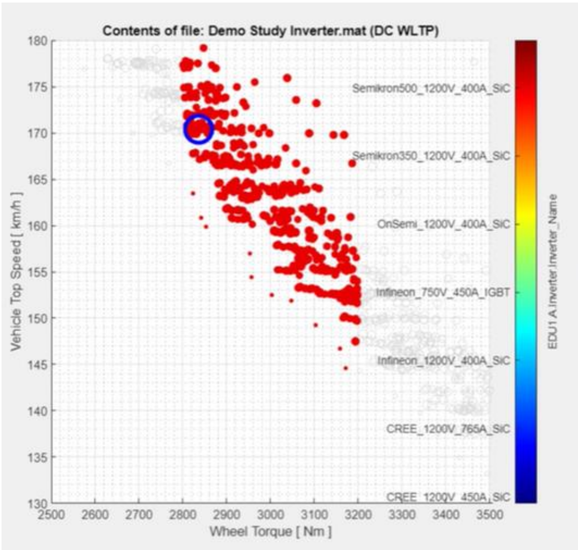

Fig. 9 Results are further downselected by applying drivecycle limits

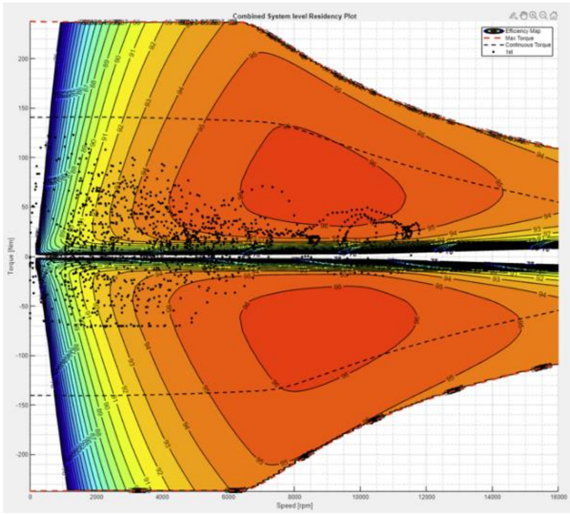

Fig. 10 Resulting efficiency map from the downselected design, with WLTP drivecycle points overlaid

consumption region of Fig. 6., and shows that the optimum system in terms of energy consumption and cost is achieved using the Infineon 1200V, 400A power module. This example shows how vehicle level design requirements can be used to drive low level component selection, and therefore inform the supply chain using ePOP. It is also clear that with this approach other technologies which impact inverter performance, such as custom power module design, power module construction and power module material, can be captured and their impact evaluated at the vehicle level, to not only inform design engineers which design options yield the optimal solution, but also to inform the supply chain which technologies are attractive for future powertrains and therefore should be invested in.

By continuing design optimization in ePOP using this power module wheel speed and torque requirements can be applied. Inspection of Fig. 8 shows that initially there is a wide spread of results according to the motor and transmission selection. In this case a WLTP drive cycle is required, when this is applied, as shown in Fig. 9, the number of viable designs reduces and a knee point can be identified that provides the vehicles required top speed with the minimum torque (circled in blue, Fig.9). Designs within this space will provide the required performance for minimum cost and energy consumption. Fig. 10 shows the efficiency map for the optimal design, with WLTP operating points overlaid. Many of the WLTP points lie in the lower efficiency regions of the efficiency map. Using ePOP allows designers to assess performance from the top level. Meaning compromises and counter intuitive outcomes such as this don’t result in designers pushing their subsystem designs into what they perceive to be improved operating regions, while compromising the rest of the system.

6 Conclusions

A key takeaway from the study is that ePOP plays a pivotal role, serving not only as a design tool but also as a strategic informant for the supply chain, offering insights into future market trends and allowing the setting of viability targets. It empowers decision-makers to define cost thresholds, enabling the feasibility of concepts even in cases where technology shows promise but costs remain a barrier. In the realm of sustainable transportation, ePOP's capabilities facilitate nuanced decision-making, ensuring alignment with industry demands and enabling the industry to progress toward a greener, more efficient future.

In the dynamic landscape of sustainable transportation, the concept of "Design for Circularity" plays a pivotal role, emphasizing the integration of circularity considerations from the initial stages of Research and Development (R&D). This approach necessitates early decisions on sustainable materials, optimized powertrains, and reduced energy consumption, fostering a holistic approach toward sustainability.

The early R&D design stage emerges as a crucial juncture, where decisions resonate across a vehicle's lifecycle. Collaborative efforts among engineers, sustainability experts, and finance professionals in this phase are essential. Every decision made in early R&D sends ripples across the entire ecosystem, emphasizing the need for a multidimensional perspective and a shared understanding among diverse disciplines.

Collaboration across the supply chain is indispensable, demanding cooperation between specialized teams within their respective silos and bridging gaps between sub-system engineers, sustainability experts, and finance professionals. The complexity deepens when it comes to key subsystems, such as eMotor, Gearbox, and Inverter, where decisions must align with both performance requirements and supply chain dynamics. Tools like ePOP provide a comprehensive framework, allowing real-time collaboration and aiding in the selection of optimal technologies.

The case study presented a comparison between IGBT and SiC inverters, showcasing the benefits of a systems-based approach. Through ePOP, thousands of powertrain architectures were evaluated, highlighting the system-level impacts of different technology selections. The study revealed that ePOP not only designs optimal systems but also informs the supply chain about future market trends.

In the face of this transformative journey, ePOP stands as the beacon guiding the automotive industry towards a sustainable future. ZeBeyond offers two main offerings: a flexible license model granting immediate access to ePOP, empowering your team with ePOP's data-driven decisions to optimize subsystems and navigate the complexities of sustainable automotive engineering efficiently. As well as a collaborative co-development option to tailor ePOP to your specific needs or challenges, be they thermal, NVH, cost or sustainability targets. Our engineers work closely with you, integrating your insights and requirements into the tool, ensuring a seamless fit for your organization's goals.

Embrace ePOP today and embark on a journey where innovation meets sustainability. Let's shape the future together and go Beyond Net Zero!"

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